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II. Abstract

II.1. English

This thesis is motivated by the need for support in considerations of robustness, reliability and safety during early design phases. The thesis deals with the question of how to codify and communicate failures and hazards, and devises measures against these. Current methods to robustness, reliability and safety reviewed have shortcomings including the complexity of using them and dependence on expert input for mitigating uncertainty and ambiguity among solution alternatives. This research is carried out using case studies: a pilot case to assess information requirements from reliability methods, and an industrial case to assess how the use of information about robustness, reliability and safety as practised by current methods influences concept development. Current methods cannot be used in early design phases due to their dependence on detailed design information for the identification of attributes of robustness, reliability and safety. The uncertainty and ambiguity that are inherent to concept development impede the evaluation and improvement of attributes of robustness, reliability and safety in early design. A taxonomy was therefore developed to assess the information about these attributes that current methods require, and to address the need for clarity about design issues that result in risks.

The concept development phase fosters ambiguity on how to satisfy requirements of robustness, reliability and safety, which is exacerbated by complexity in the individual solution alternatives. This prompts designers to reuse working principles that are inherently flawed, as they are liable to disturbances, failures and hazards. To address this issue, an approach based upon individual records of early design issues consists of comparing failures and benefits from prior working principles, before making a decision, and improving the more suitable alternatives through this feedback. Workshops were conducted with design practitioners to evaluate the potential of the approach and to simulate decision-making and gain feedback on a proof-of-concept basis. The evaluation has demonstrated that the use of individual records on failures and benefits of solution alternatives successfully averted the repeated use of flawed working principles and identified the effective design solutions of the outstanding issues.

Keywords: Design for X, knowledge management, codification, use of information

II.2. Dansk

Denne afhandling er motiveret af behovet for støtte, når man arbejder med oplysninger om produkters robusthed, pålidelighed og sikkerhed i tidlige designfaser. Afhandlingen beskæftiger sig med spørgsmålet om, hvordan man kan kodificere og kommunikere usikkerhed, fejl og farer, og udtænke foranstaltninger imod disse. De nuværende metoder til at bedømme produkters robusthed, pålidelighed og sikkerhed har mange mangler. Det er bl.a. meget kompliceret at bruge disse metoder, og metoderne er afhængige af input fra eksperter for at reducere usikkerhed og uklarhed blandt løsningsalternativerne. Dette forskningsprojekt udføres ved anvendelse af case studier: en pilot case med det formål at vurdere oplysningskravene fra pålidelighedsmetoder, og en industriel sag for at vurdere, hvordan brugen af oplysninger om robusthed, pålidelighed og sikkerhed, som det praktiseres med de nuværende metoder, påvirker konceptudvikling. De nuværende metoder kan ikke bruges i de tidlige designfaser på grund af deres afhængighed af detaljeret design information til identifikation af robusthed, pålidelighed og sikkerhed.

Den usikkerhed og flertydighed, som er en naturlig del af begrebet udvikling, hæmmer evaluering og forbedring af robusthed, pålidelighed og sikkerhed i den tidlige designfase. En specifik taksonomi blev derfor udviklet til at vurdere, hvilke oplysninger om disse egenskaber de nuværende metoder kræver med henblik på at imødekomme behovet for klarhed omkring designløsninger, som skaber risici under konceptudvikling.

Udformningen af en række løsningsalternativer i konceptudviklingen fremmer flertydighed med hensyn til, hvordan man tilfredsstiller kravene til robusthed, pålidelighed og sikkerhed, som forværres af kompleksitet i individuelle løsningsalternativer. Dette foranlediger designere til gentagne gange at bruge mangelfulde arbejdsprincipper, der medfører usikkerhed, fejl og risici. For at løse dette problem, består en approach baseret på individuelle opgørelser over tidlige design spørgsmål i at sammenligne fejl og fordele blandt tidligere arbejdsprincipper, inden der træffes en beslutning, og forbedre de mere passende alternativer ved hjælp af denne sammenligning. Der blev afholdt workshops med produktudviklere til at vurdere potentialet af denne approach og til at simulere beslutningsprocessen og derved få feedback på en proof-of-concept basis. Evalueringen har vist, at brugen af individuelle registreringer af fejl og fordele ved løsningsalternativerne forhindrede den gentagne brug af mangelfulde arbejdsprincipper og identificerede effektive designløsninger på udestående udfordringer.

Nøgleord: Design for X, vidensdeling, kodificering, brug af information

II.3. Português

A necessidade de suporte às considerações de robustez, confiabilidade e segurança motiva o trabalho apresentado nesta tese. Este projeto desenvolve a codificação e a comunicação de falhas e perigos no projeto de sistemas mecânicos, e propõe medidas para melhorar esses processos. Os métodos atuais para robustez, confiabilidade e segurança aqui revisados têm desempenho insuficiente para mitigar a incerteza e a ambiguidade entre alternativas de solução, por conta da complexidade de seu uso e de sua dependência de conhecimento especializado. Esta pesquisa é executada mediante estudos de caso: um caso piloto para availar os requisitos de informação dos métodos de confiabilidade, e um caso na indústria para estudar como o uso de informação sobre robustez, confiabilidade e segurança em métodos atuais da prática projetual influencia a fase de projeto conceitual. Os métodos atuais aqui availados não são adaptados para o uso em fases precoces de projeto porque dependem de informações detalhadas de projeto para a identificação de atributos de robustez, confiabilidade e segurança nas soluções em desenvolvimento. A incerteza e a ambiguidade inerentes ao projeto conceitual impedem a availação e o melhoramento de atributos de robustez, confiabilidade e segurança. Foi desenvolvida neste trabalho uma taxonomia, para avaliar os requisitos dos métodos atuais em informação sobre estes atributos, e para responder à necessidade de clareza sobre problemas de projeto que resultam em riscos.

A fase de projeto conceitual cria ambiguidade em formas de satisfazer requisitos robustez, confiabilidade e segurança, o que piora com a complexidade de projeto das alternativas de solução individuais. Isto leva projetistas a reutilizar princípios de solução que são inerentemente falhos, porque são sensíveis à ocorrência de perturbações, falhas e perigos. Para trabalhar este problema, uma abordagem baseada em registros individuais de problemas de concepções consiste na comparação de falhas e benefícios de princípios de solução já desenvolvidos, antes de tomar uma decisão, e no melhoramento das alternativas de solução melhor ajustadas aos requisitos. Workshops foram conduzidos com engenheiros projetistas para availar o potencial da abordagem e para simular tomadas de decisão, para obter resultados em prova-de-conceito. A avaliação demonstrou que o uso de registros individuais sobre falhas e benefícios de alternativas de solução evitou o uso repetido de princípios de solução falhos, e identificou soluções eficazes de projeto para os problemas remanescentes.

Palavras-chave: Projeto para X, gestão de conhecimento, codificação, uso de informação

III. Glossary

Attribute: a consideration made by stakeholders and customers in the product lifecycle when they assign value to the design of a product. Example: reciclablility.

Context-dependent: a set of inter-related conditions in which something exists or occurs, which influence the perception of meaning on a sign. Example: the optimization of an electric circuit with robust design does not ensure its safety against hazards.

Design characteristic: a quality that makes a product distinctive from others, which designers can control through the design activity. Example: gearing ratio of a power take-off gearbox.

Design information: information that conveys definite characteristics and/or properties of a product being designed. Example: a report with drawings and design characteristics of an engine crankcase.

Design issue: a set of relationships among characteristics and properties of a product being designed, which affects the performance of a system unit in performing its function. Example: the buckling stress limit for permanent deformation of a steel column.

Design method: a set of instructions on how to perform activities to proceed one or more steps in a design process (Buur, 1990). Example: the use of morphological matrices to represent all options of working principles and alternatives to a part union gun.

Design model: an element that reproduces characteristics and properties of the designer's idea of the product to be designed (Buur & Andreasen, 1989).

Design practice: the context where knowledge is used by designers to elicit, generate, process, communicate, and select characteristics and properties of the product being designed. Example: the use of engineering and design knowledge to perform cost assessments.

Design principle: knowledge of general characteristics of design solutions that favour advantageous solutions to certain product attributes (Matthiassen, 1997).

Design strategy: a planned course of action undertaken to generate, modify or optimize design characteristics in carrying out a task that is oriented by the purposes of product quality. Example: the identification of cause-effect relationships from mechanical stress formulations.

Design task: a single procedure carried out to process design information for the purpose of a planned design process. Example: the construction of a scale model.

Early phases: activities and tasks in the design process that include the preliminary definition of design requirements, technologies and embodiments for a new product.

Evaluation method: a design method used to generate judgment about product attributes on whether they satisfy expectations about quality. Example: HAZOP identifies causes of hazards.

Expert knowledge: understanding about facts or issues that is accumulated from personal experiences in performing a design activity. Example: expert knowledge about the dynamic properties of a wind turbine blade undergoing a stochastic distribution of wind gusts.

Failure mode: appearance, manner or form in which failure manifests in a component or system unit manifests (Bloch & Geitner, 1990)

Feasibility: the capability of a solution alternative for a product to performing intended functions within values close enough to requirements so that they are acceptable.
Example: the feasibility of a design that performs oil drilling under the salt layer is determined by its ability to avert obstacles and withstand temperature and pressure conditions.

Feedback: the phenomenon by which knowledge about a design decision is supposed to affect the reuse of knowledge to design a new solution alternative during early design phases.

Force path: the property of a mechanical system that is defined by the chain of force transfers that carries the main components of an input force to carry out an action at the end component.

Heuristic: something that involves an aid or serves as guidance to learning, discovery or problem-solving derived from trial-and-error cycles and empirical experience.

Technical risk: uncertainty on whether a product design is technologically feasible and will perform as expected (Unger, 2003).

Uncertainty: deficiency of information related to knowing or understanding an event, its likelihood and its consequences to a desired objective (ISO Guide 73, 2009)

Working principle: it is a combination between physical laws that govern a phenomenon and characteristics of geometry and material in components that enables a functional transformation.

IV. Table of Contents

Chapter 1 - Introduction

Manufacturing companies establish reputation in the market by producing solutions that are less sensitive to circumstances and/or conditions in their lifecycle. In order to deliver quality through product development, it is essential to communicate details of its performance during the design process. Failure to do so is a significant cause of design flaws (Gries, 2007). This research focuses on the communication of the following quality attributes in early phases of the design process:

- Robustness: the product performs in the best way expected when used;
- Reliability: the product works during for most of time it is needed; and
- Safety: the product causes the least harm upon an accident.

Table 1 gives examples of performance issues with effect to robustness, reliability and safety in different mechanical systems:

Table 1 – Examples of design issues and their effect on robustness, reliability and safety

Heavy truck air suspension	Wind turbine drivetrain	Camera diaphragm	Injection mechanism
Disturbances			
Load distribution, ground relief	Wind direction, wind gusts, hub loads	Temperature, air humidity	Forces, air humidity, temperature
Issue			
Internal pressure cycles on shock absorbers, flexure loads on airbags	Flexure loads from shaft to bearings, contact stress on gear surfaces	Differential expansion, foreign objects between diaphragm sheets	Differential expansion causes misalignment and backlash on parts
Effect			
Lack of robustness to pressure cycles and flexure loads	Lack of reliability over cyclic loads of stress and deflection	Lack of robustness to temperature and humidity variations	Lack of safety over misalignment and dose control
Failure mode			
Increased vibration loads on structure, leaking on airbags	Excessive deflection, increased wear on bearings and gears	Friction between diaphragm sheets, irregular aperture	Hard or irregular injection, difficulty to control desired amount
Consequence			
Degraded load capacity causes downtime to truck	Stoppage on wear causes downtime to wind turbine	Stuck diaphragm makes camera unusable	Wrong amount against prescribed a risk to health
Worst case			
Failure on traffic causes accident with damage	Lubricant leak + spark causes fire on wind turbine	No particular damage outside the camera	End-of-dose failure causes overdose, sickness

1.1. Motivation

This research focuses upon supporting the systematic use of information of robustness, reliability and safety (R2S) to support engineering design processes. Addressing R2S attributes through the design process benefits the treatment of technical risks in design projects, as these attributes are part of product quality and are thus criteria for intended functional performance (Hammer, 1980; Mørup, 1993; Matthiassen, 1997). The use of codified knowledge about R2S attributes benefits the following tasks in the design process:

- Making decisions on priority assignments, and
- Engaging the chosen priorities and solving outstanding issues.

Experience demonstrates the usefulness of systematically aggregated information about performance attributes in product design, having as it does a positive effect on product quality and risk reduction. Methods for R2S such as HAZOP gained widespread acceptance in industry (Kletz, 1997); their approach to declaring information about R2S has effectively minimized losses in productivity and quality in industry. However, the approach in methods like HAZOP has a few shortcomings that require attention.

The need to choose among several alternatives during early design phases, such as concept design, makes current R2S methods difficult to use. These methods focus on problems from component details, hence current methods for R2S demand too many resources in specialized knowledge, design information, and team headcount. Even for products with few components, it takes too long to generate and use design information; this restricts the use of current methods to later design phases, where changes to the design increase costs exponentially. As current methods are not suitable for the improvement of working principles, this lack of support to early design phases is detrimental to quality and innovation.

Current practice to elicit and codify R2S attributes in early design phases demands significant expertise, as the skills of reasoning and communication on product functionality require learning by experience over time. As this knowledge is difficult to share, current use of information about R2S in early phases does not guarantee the rejection of flawed designs or the positive implementation of feedback from prior failures. Design teams thus need several iterations to reach the principle solution, which increases development costs. Managers become afraid of exploring new mechanical solutions, as current practice fails to benefit from explicit knowledge about early designs, with information about R2S as quality criteria.

1.2. Aim and objectives

This research aims to address the lack of systematic support from R2S methods during early design phases. This includes the identification of problems with the use of information in current methods, towards practice for R2S attributes in early design phases; and the synthesis of a systematic approach to improving the use of information about R2S in early design phases. This thesis makes a contribution to:

- Researchers working in the context of R2S issues in engineering design,
- Engineering designers developing a product in its early phases, and
- Industry specialists in R2S supporting the management of technical risks.

To pursue the link between the codification of information about R2S and its support to innovation, this study uses research questions as primary directives. Table 2 displays the research questions and the respective objectives of this study.

Table 2 – Aim of this research, specific objectives and research questions

Aim of this research: **To improve the use of information about robustness, reliability and safety (R2S) identifying for/against characteristics of solution alternatives during early design phases**			
Motivations			
(1) Literature: ambiguity on whether current R2S methods are suitable to early phases	**(2) Industry + findings**: need to assess use of information about R2S, its influence in practice	**(3) Industry + findings**: need to help current practice improve R2S attributes	**(4) Industry + findings**: support to decisions and feedback on information about R2S in alternatives
Specific objectives			
To characterize how current methods for R2S use information from product design to assess risks to its functionality.	To understand how current design practice influences concept design to address R2S attributes.	To propose a novel approach for R2S to assist designers in using available information in concept design.	To validate the proposed approach on how it improves the ability of design teams to address R2S attributes.
Research questions			
What information about product design do current methods for R2S need to generate information about R2S in a product?	**How does information about R2S from concept design influence practice to improve R2S on solution alternatives?**	**How to model information about R2S in solution alternatives for methods that elicit practice to improve R2S during concept design?**	**How does the proposed model of information about R2S support practice to improve R2S during concept design from a method for R2S?**

The papers communicate partial results obtained through the studies to the research questions hereby defined. The pursuit of Question 1 about the information requirement of current methods is motivated by ambiguity on whether and how R2S methods are suitable to early design (Glossop, Ioannides, & Gould, Review of hazard identification techniques, 2005).

To characterize the suitability of R2S methods to early design phases and generate preliminary criteria for understanding on the practical context, the familiarity with current methods for R2S attributes served as a basis for assessing information requirements for using R2S methods in early phases of the design process in paper I (Marini, Restrepo, & Ahmed, 2010). The assessment of the suitability of current R2S methods to early design phases was conducted through a comprehensive study of the types of information involved, their sources, and information in that is unavailable in early design phases, which is described in paper II (Marini & Ahmed-Kristensen, 2013).

To assess the actual use of information about R2S in early phases, and its influence on addressing R2S attributes when developing alternatives, research question (2) led to an industrial case study investigating current practice. Here, a longitudinal study of the methods and resources used in industrial practice for early design phases led to findings about the selection of alternatives, in paper III (Marini, Ahmed-Kristensen, & Restrepo, 2011). The assessment of R2S evaluation methods and their influence on early design phases developed awareness of the importance of decision-making and feedback for converging to satisfactory solution principles, in paper IV (Marini & Ahmed-Kristensen, 2012).

The findings stimulated a debate on the influence of R2S evaluation methods on product development strategy, as described in paper V (Marini & Ahmed-Kristensen, 2013): team managers are responsible for decision on the selection of solution alternatives; designs once rejected were still reused later in the design process. These findings provide a foundation for the development of a the support tool for early design phases as defined in question (3), and the validation of this proposition as defined in question (4). Understanding the influence of current practice enabled the elicitation of requirements and feedback for proposing a design tool to support R2S attributes in early design phases.

These findings established the needs of support in early phases of the design process, which have driven the development of the design tool as support for knowledge reuse. The results from this development, and the findings from verifying the tool, were consolidated into a discussion on the design tool for decision-making and knowledge reuse in early design phases, and presented in paper VI (Marini & Ahmed-Kristensen, 2013). The study describes how the tool is designed in requirements and concept, and verified through a use simulation of how designers would engage in selecting alternatives in early design phases.

1.3. Structure of the thesis

The use of information about R2S was investigated through different experiential contexts:

- Study of previous literature in engineering design and R2S methods
- Pilot case study about information in current R2S methods, and
- Longitudinal case study on concept development in industry

This thesis develops knowledge on using information about R2S in early design phases by declaring foundations, pursuing awareness of issues and fostering insight. Table 3 presents the structure of this thesis for introduction to the context of study. This report starts with three general chapters discussing the motivation of this research (Introduction), the background with related topics from theory and prior work (Literature review), and then its methodological foundation (Research method).

Table 3 – Research questions and structure of this thesis – part I

1. Introduction	Introduces the research motivation, formulates research objectives and describes the structure of the thesis
2. Literature review	Introduces field delimitations and key definitions; identifies knowledge about R2S attributes, their codification and use in models and methods for R2S; and concludes with the implications from literature for research questions.
3. Research method	Introduces the research object; describes the methodological basis used; presents the strategies used to perform the research; and presents the research methods used to generate deliverables

After these chapters, the thesis presents the contribution from the study. This section provides an overview about the codification of information about R2S in early design phases, and presents the research papers that give more detail about the findings. This part of the thesis is then structured around the content of Table 4, which relates the research questions to the core contribution. At a higher level, this is based upon the methodological framework proposed in DRM for design research (Blessing & Chakrabarti, 2007). This supported the development of the studies contained in the papers, which demonstrate the findings on which this study contributes knowledge.

This thesis then concludes with an overall discussion of the results (discussion), some reflections from practice, and a comparison with similar work pointing out future development opportunities. Table 5 displays the complementary items in this thesis with such reflections.

Table 4 – Research questions and structure of this thesis – part II

4. Research contribution		Research question 1	Research question 2	Research question 3	Research question 4	
		What information about product design do current methods for R2S need to generate information about R2S in a product?	**How does information about R2S from concept design influence practice to improve R2S on solution alternatives?**	**How to model information about R2S in solution alternatives for methods that elicit practice to improve R2S during concept design?**	**How does the proposed model of information about R2S elicit practice to improve R2S during concept design from a method for R2S?**	**Research questions**
Overall		The research contribution; how studies are reported in papers; how papers conclude stages of the research methodology; and how the findings in individual papers contribute to the overall result of the research				
Preliminary criteria	**Paper I**	Information requirements of current R2S methods against design models from early design phases				**Preliminary criteria**
	Paper II	Sources of design information, missing details in early design phases and use by current R2S methods				
Descriptive study I	**Paper III**		Use of methods for R2S in early phases of industry project and their influence on decisions about alternatives			**Descriptive study I**
	Paper IV		Decision-making and feedback as critical areas for deploying knowledge-based support in early design phases			
	Paper V		Use of engineering knowledge in evaluation methods and its influence on carrying out product development	Factors in the design process that influence the effectiveness of current methods for R2S in early phases		
Prescriptive	**Paper VI**			Design process requirements and prescriptive study for developing support to handle R2S attributes in early design phases	Early feedback from prescriptive study for R2S attributes in early phases and verification of the practical use of a design tool	**Descriptive II**

Table 5 – Research questions and structure of this thesis – part III

7. R2S in early design phases	Compares the findings on the influence of information and practice about R2S issues, assesses the formulation of the design approach against current practice, and discusses the design approach and its proof-of-concept validation against the state-of-the-art.
8. Conclusion	Comes to a conclusion on the degree of verification of results obtained against the research aim and its specific objectives, and suggests future work in continuation of current efforts.

1.4. Summary

This chapter identified the following needs:

- categorising types of information on robustness, reliability and safety (R2S) in engineering design, and,
- giving support for the use of information about R2S attributes in early phases of the design process.

The resource demands from current methods for R2S and the experience required to address R2S attributes adequately in early phases highlight the need to develop systematic support to early design phases. Objectives were established and refined through this research, motivated by shared interests between academy and industry to investigate shortcomings with current methods and practice for R2S, and to support the use of information about R2S. The following research questions were then proposed as shown in Table 6, also displaying the methodology stages and the academic content on which this contribution has been developed.

Table 6 – Research questions of this thesis – summary

Research questions			
(1) **What information about product design do current methods for R2S need to generate information about R2S in a product?**	**(2)** **How does information about R2S from concept design influence practice to improve R2S on solution alternatives?**	**(3)** **How to model information about R2S in solution alternatives for methods that elicit practice to improve R2S during concept design?**	**(4)** **How does the proposed model of information about R2S support practice to improve R2S during concept design from a method for R2S?**
Papers I and II	**Papers III, IV and V**	**Papers V and VI**	**Paper VI**

Chapter 2 - Literature review

This chapter presents the use of information about robustness, reliability and safety (R2S) in engineering design as understood in literature. Field delimitations introduce the context of this research by identifying knowledge about the following areas: design methods for risk and reliability; codification of information in engineering design; knowledge in decision-making; and feedback and design reuse. Conclusions discuss the implications of these areas using information about R2S. Table 7 presents examples and the sections where they are presented.

Table 7 – Research context and delimitations in this literature review

Research context: **The phase of the design process that generates solution alternatives, identifies attributes for/against their success, and manages these to ensure a solution is achieved**
• **Design methods for risk and reliability – *section 2.1*** Methods for analysis of product functions and operation scenarios (ISO 31010, 2010). • **Codification of information in engineering design – *section 2.2*** Taxonomies to organize design information and models to represent product design. • **Knowledge management issues in early design phases – *section 2.3*** Views about the use of expertise and information in early design phases • **Use of knowledge in decision-making and feedback – *section 2.4*** Dynamics of decision-making and design feedback.

Risk and reliability methods draw support from knowledge elicited in early design phases. These are described in this review as follows:

Methods regarding risk and reliability are used to support quality with assessments on product functions and use scenarios (ISO 31010, 2010): Functional analysis methods such as FMEA work with individual product functions (MIL-STD 1629A, 1980); scenario analysis methods such as FTA work with behaviour that escalates to product risks (Vesely et al., 1981). Information codes in engineering design are used to represent and organize forms of design knowledge. The model-based approach regards the communication of product attributes in the design process through models, and the knowledge-based approach focuses the organization and management of design information by structures such as taxonomies for indexing engineering knowledge (Ahmed, Kim, & Wallace, 2007).

Knowledge from information and methods to risk and reliability is intended for use with the design and implementation of products. Current understanding about its management and use is discussed in the following topics:

Engineering knowledge management considers the acquisition and use of knowledge as a means of generating product designs from early design phases. This includes the collection of prior expertise and information from previous projects in early product development (Markus, 2001), and the incorporation of previously developed working principles and components into the design of new products (Duffy, Duffy, & MacCallum, 1995). The use of knowledge in making decisions and suggesting improvements during early phases takes account of the dynamics of design decision-making together with feedback to improved designs. This comprises: assessing the factors and circumstances that influence decision-making in the design process (Dwarakanath & Wallace, 1995), and the issues related to the effective use of feedback (Busby, 1998) as response in improving design alternatives.

The chapter concludes by discussing the above-mentioned areas on the research questions stated in Chapter 1, on the influence of current contributions to research questions.

2.1. Design methods for risk and reliability

This section describes two types of methods for risk and reliability as defined by the ISO 31010 classification – with functional analysis and scenario analysis categories. Methods of *functional analysis* such as FMECA (MIL-STD 1629A, 1980; EN 60812, 2006) generate information about R2S in product functions by eliciting information about product design characteristics and their influence on intended performance are first described. Then, *scenario analysis* methods such as FTA (Vesely, Goldberg, Roberts, & Haasl, 1981; EN 61025, 2007) consist of symbolic representations with underlying logical models that represent how information about R2S of solutions influences overall performance.

2.1.1. Methods of functional analysis

The relevance of methods for the functional analysis of R2S attributes resides in their ability to characterize functional properties of systems, in the factors (hazards and flaws) which have a detrimental effect, and in the measures used to address these. Each different method within this classification is commented on in regard to its approach to elicit information about R2S from functional elements of systems and its relevance to the design process. The discussion focuses on how R2S methods translate characteristics of product functions into information about R2S, and on their limitations in planning design improvements from the information they use.

The Failure Mode, Effects and Criticality Analysis (FMECA) evolved from its birth in the aerospace sector (Dhillon, 1999). It became an essential design tool (MIL-STD 1629A, 1980) as a resource for supporting quality and accountability, due to its inquiry process about R2S issues. All queries consider the system decomposition carried out before the FMECA procedure; this includes component characteristics, their operation regime, and possible interactions with the environment and external agents. Assessing the priority of individual issues, FMECA ranks improvements for R2S attributes. The method assumes all failure modes to be independent and therefore does not address common-cause failures (EN 60812, 2006).

The method's requirements for data, the need for expert judgement and the amount of work involved in assembling the analysis require a frozen design concept, without further changes at the system level under consideration. In addition to this, expert judgment is needed to assess the severity and criticality of failure modes if a quantitative assessment is not possible (Glossop, Ioannides, & Gould, Review of hazard identification techniques, 2005). In early design phases, the lack of information about system components together with the number of alternatives that need to be considered make FMECA an unfeasible choice for using information about R2S. The method is better suited to detailed design phases, where the geometry and material properties have been defined together with manufacturing specifications.

Dealing with functional definitions and the influences of their implementation, Hazard and Operability Studies (HAZOP) was created to identify hazards and operational deficiencies in chemical processes (Swann & Preston, 1995). The distinguishing feature of HAZOP is its focus on what could go wrong with functions (design intent) and the possible consequences rather than on the advantages or objectives achieved by a design (Kletz, 1997). A necessary condition for using HAZOP is to start from an adequate design description, which characterizes the system in its functions, elements and flows. A flow diagram input is needed as input for HAZOP, as all conditions are assessed upon system flows.

With such information at hand, HAZOP entails the use of keywords as cues to elicit expert knowledge. The aim of these keywords is to encourage the use of prior expertise to assess the implications from particular episodes of change in system states (BS IEC 61882, 2001). The use of working parameters and keywords on system functions instead of components enables HAZOP to be used while the design is still under development. However, Swann and Preston recommend the use of HAZOP once component characteristics have been established in a detailed design phase. Another issue consists of expert input that is required to guide the translation of keywords into system deviations and their effects.

FMECA considers deviations in individual parameters and does not address hazards resulting from interactions among parameters in different system functions (BS IEC 61882, 2001). While essential input to HAZOP is already defined by early design phases, the lack of documentation on detailed characteristics means that it is not possible to obtain all relevant information about R2S for use with the method.

Design Review Based on Failure Mode (DRBFM) carries a specific approach to design review, to ensure engineers realize the outstanding issues involved in changing product designs and mitigate them (Shimizu, Imagawa, & Noguchi, 2003). Starting from a system hierarchy, DRBFM provides a protocol for implementing design reviews which takes advantage of common methods such as FTA and FMECA in order to assess emerging issues according to the need to change a design. Figure 1 shows examples from the design review of a hair dryer and its component structure, which illustrate the failure mode of interest (cracking in the motor holder) and point out the mechanisms of the problem. This elicits possible causes of failure in the system structure, identifying causes of problems with the motor holder in the hair dryer (Shimizu, Otsuka, & Noguchi, 2007).

The diagnosis sheet uses a format – shown in Figure 2 – similar to those of FMECA and HAZOP, and incorporates information about the system structure and the associated root causes of failure. Once the failure modes and their causes are assembled, the design review process works with the characteristics of individual components. The use of models displaying the characteristics of interest in failure modes works to elicit points of concern that need to be addressed by immediate actions (current steps, and by recommended actions for further reviews. The spreadsheet format is embodied in large print; designers can then use post-it notes with their thoughts within the scope of the review.

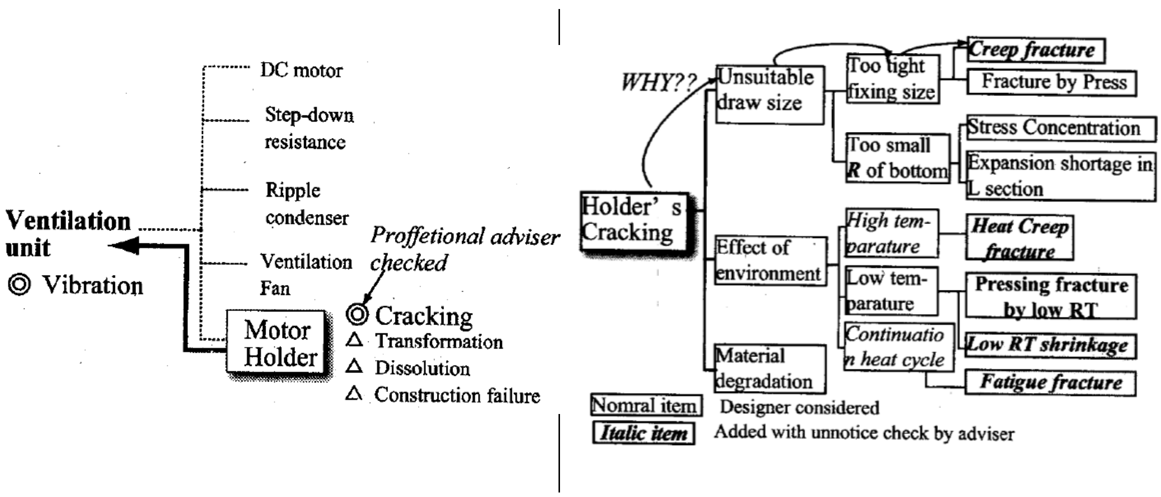

Figure 1 – System hierarchy, fault assessment to DRBFM (Shimizu, Otsuka, & Noguchi, 2007)

It can be used to address system, part, interface and production issues in different design stages, which makes DRBFM a design tool of cumulative use in the same way as QFD (Hauser & Clausing, 1988). This works to accumulate knowledge needed to explain the reasons of component characteristics. As DRBFM involves a detailed design review of the impacts from changes in local assemblies, its scope of use in early stages is largely restricted. The method is not intended as a system-wide evaluation, but focuses rather on specific points of concern due to changes in a specific subsystem.

Component Name／Changes	Function	Concerns Regarding Change (Failure Mode)		When and How Concern Points appear		Effect to Customer (System)	Importance
		Potential Failure Mode due to Change	Any Other Concerns? (DRBFM)	Root Cause / Dominant Cause	Any Other Consideration for Cause? (DRBFM)		

Current Design Steps to avoid Concerns (inc. Design Rule, Design Standard & Check Items)	Recommended Actions (Results of DRBFM)						Action Results
	Items to Reflect in "Design"	Resp. & Dead-line	Items to Reflect in "Evaluation"	Resp. & Dead-line	Items to Reflect in "Production Process"	Resp. & Dead-line	

Figure 2 – Sheet format and protocol to DRBFM (Shimizu, Imagawa, & Noguchi, 2003)

Hence, it provides a limited overview of the system functions and components needed in early stages. Performed on large subsystems, DRBFM can be laborious if the focus is not restricted to local impacts from design efforts in subsystems with a limited number of components. As its formulation aims to make incremental changes to component design, the method requires awareness of interactions with components beyond the scope of review. Hence, its use on early phases should address the impacts from the changed subsystem as a whole, serving as a prior direction to further efforts in detail design and process ramp-up phases.

2.1.2. Scenario analysis

Scenario analysis methods for R2S are characterized by a common approach that analyses system components and their links, to verify the effect of faults in system functionality. They work by eliciting incidents to R2S attributes in individual system elements, assessing their role and escalation to system-wide impacts, and assigning priority to the specific issues with highest impact. Thus, the relevance of scenario analysis methods for R2S resides in their ability to characterize issues according to how they progress while making detrimental effects to R2S attributes.

Fault Tree Analysis (FTA) was first developed as a support for ensuring safety in the nuclear industry (Vesely, Goldberg, Roberts, & Haasl, 1981). It is intended to communicate and analyse how connections between components cause faults to evolve into catastrophic system failures. Events characterize components and their working states, where component and intermediate faults are described. Gates work in defining system relationships in two senses: first, the system decomposition into subsystems and components; and, second, the interdependence between lower-level faults and system-level faults.

A model of Boolean algebra calculations represents the problem for finding individual combinations of faults needed for the incident to escalate to the top event – the system-wide failure. The assumption that all events in the tree are independent applies to the events combined in the cutsets. The factors that influence the use of fault trees are: (a) the system levels, links and number of components; (b) the behaviour variety in components and links; and (c) behaviour timing regardless of the commonality of causes or modes of faults.

Branches from different gates may not communicate, which prevents the assessment of bad interactions. In addition, the fault tree does not allow timing considerations between events in the same level. FTA requires a complete design definition (Glossop, Ioannides, & Gould, 2005), at least at the system level, so it should be continuously developed (EN 61025, 2007). This includes FTAs at system level to discover scenarios in product architectures, which are evolved toward component FTAs in late design phases addressing issues in product assemblies.

In a contrasting approach to FTA, Event Tree Analysis (ETA) assesses of the implications of a single hazardous event; it was first used in the nuclear industry to assess the effectiveness of protective measures against accidents (Rasmussen & Levine, 1975). The difference in event trees from fault trees is that the problem formulation diverges onto several outcomes instead of converging into a single consequence. Event tree start with an initiating event, and develop through scenarios modelling the event chain; this requires thorough system analyses to identify the event chains that describe the possible outcomes of the first event.

Events with single outcomes need to be avoided and common-cause failures only work if they influence the same chain (Levine & Vesely, 1976). The difficulty in using ETAs consists in the extensive knowledge needed to carry out the analysis. The arrangement of system components creates difficulties for the establishment of failure scenarios, as the positioning of outcomes influences its interpretation (Rasmussen, 1981). ETAs do not include considerations on behaviour timing between components; each branch is considered to be an independent path, so interactions between events through the tree are not considered.

Hence, the analysis should consider a complete system design, as components and their links need to be characterized. A system-based event tree is possible as long as the architecture in components and relationships is available. The more defined the characteristics and behaviour of system components are enables ETA to provide more precise assessments incidents, in a similar way to using FMECA.

Safety analyses based upon reachability computations on the node sequence are used to identify system conflicts giving rise to hazards. Scenario analyses with Petri nets are highly valued due to their ability to represent parallel sequences, especially when implemented with software tools. This takes into consideration the timing and simultaneity by which problems escalate. Petri nets require a compromise between their accuracy and their complexity to reproduce timing and simultaneity (Kontogiannis, Leopoulos, & Marmaras, 2000). Proper timing in Petri nets requires knowledge of the component-level behaviour, with a more complex formality than those in fault tree and event tree analyses; this requires extensive training for proper use of the tool.

2.2. Models of design information

This section presents two distinct types of models of engineering knowledge and product design: knowledge taxonomies and design models, which work to organize and represent information about product design. *Knowledge taxonomies*, such as for robustness strategies (Jugulum & Frey, 2007), take on a given domain like robust design with hierarchies of concepts, intended to help classify elements that are relevant to a design activity. Secondly, *design models,* such as freehand sketches (Hubka, Andreasen, & Eder, 1988), are presented; these represent particular characteristics of the product, intended to communicate the intended solution and process to achieve quality.

2.2.1. Knowledge taxonomies

Knowledge taxonomies aim to facilitate access to knowledge by classifying and indexing information that is used in the design process (Kuffner & Ullman, 1991). Taxonomies model shared concepts that create awareness of accumulated experience that is critical for organizations, as they have a positive effect on sharing information (Zander & Kogut, 1995). This section focuses on taxonomies applied to engineering design with the aim of assisting the acquisition and reuse of engineering knowledge. They work by organizing a domain into concepts with relevant relationships for representing situations and drawing strategies, such as with a damping issue within the design of a new suspension system.

A knowledge indexing framework was used to make a diary of design activities, where information on design tasks was organized into four overall classes: descriptor, subject class, criticality and level of detail. The framework enabled debating alternatives, using strategies and defining evaluation methods under the miscellaneous descriptor; developed for recording design activities, it was embedded into the DEDAL tool to help track the rationale of concept designs (Baudin, Gevins, & Baya, 1993). However, indexing becomes cumbersome, as the underlying structure of concepts and attributes is not transparent. With 'performance' as the closest term, hence the codification structure does not address information about R2S directly.

Systematic methodologies advocate the use of *verb+noun* clauses to abstract function definitions to make freedom for innovative solutions; however, they neglect the implementation of transfer relationships through working principles. Their coding requires the use of additional tables as dictionaries to explain the modes of action in working principles associated with specific functions (Pahl, Beitz, Feldhusen, & Grote, 2007). To overcome inconsistencies in the definition of sub-functions, the functional basis consists of a standard vocabulary for elementary functions to support functional modelling (Stone & Wood, 2000). The reconciled functional basis is decomposed into three levels to provide alternative vocabulary for intended functionality (Hirtz, Stone, McAdams, Szykman, & Wood, 2001).

The functional basis was verified within the aerospace domain, where at least half of 9990 terms in the industrial setting were found to match positively (Ahmed & Wallace, 2003). The non-matching half resulted from the use of component-specific vocabulary. For instance, one function of the turbine internal casing of an aero-engine was declared as '*define flow path to combustor and nozzle guide vane*'. This demonstrates the difficulty to use generic concepts to express purpose, without losing information on attributes such as constraints, conditions or functionality. The matching between functions by designers and concepts may fail to address information to R2S, as we saw with the loss of information about attributes mentioned above.

Information about R2S attributes is involved in the taxonomy for identifying failure modes in conceptual design (Tumer, Stone, & Bell, 2003); it is based upon an inherent relation between failure modes in components and the functions impaired. The taxonomy treats failure modes by similarities between its concepts and descriptions of incidents from experience. Its indexing of failure modes supports the retrieval of information on failure occurrences linked to functions where occurrences such as '*high-cycle fatigue in the drive shaft*' are stored in failure mode (*fatigue),* component (*shaft*), function (*transfer)* and flow *(mechanical energy)* databases (Tumer & Stone, 2003).

The use of concepts with generic vocabulary results in the same loss of attributes as with the functional basis; knowledge about failure modes must be extracted from individual experience by decoding the concepts. While the approach treats trade-off relations in components, it neither embodies failure modes nor carries other attributes in information about R2S, such as likely effects from failure modes; it has not been tested in design situations to verify whether it supports knowledge reuse in industry. The flexibility necessary to address design situations in corporate environments comes from industrial experience synthesized into categories to index engineering knowledge. EDIT (Engineering Design Integrated Taxonomy) aims to support the search and reuse of design information by indexing characteristics of design situations.

Its structure provides transparent indexing concepts comprising *Type-of* information classes that supply information regarding the context engineers need to know about engineering design practice (Ahmed, 2005). Experiments within an aerospace company performed by Ahmed (2005) showed that the taxonomy could index over 600 design descriptions in the product database: with *product* and *issue* each comprising nine out of ten references, *design process* being used in half of the references, and *function* in two out of each ten references. Table 8 shows EDIT decomposed to second-level ´concepts.

Table 8 – Formulation of EDIT Taxonomy to second-level concepts, from (Ahmed, 2005)

Function	Product	Issue	Design process
Function	Assembly	Functional requirement	Phase
Flow	Component	Lifecycle requirement	Task
	Interface	Product characteristic	
		Interface-environment	

In this context, the interpretation of concepts in classes and sub-classes is a major concern both in theory and in practice (Ahmed, Kim, & Wallace, 2007); the applicability of concepts in EDIT across industrial environments helps to establish the context to retrieve and promotes the use of relevant design information. However, the effective use of transparent taxonomies depends on whether users can interpret their concepts and relations, which determines the suitability of attribute concepts in sub-classes for use across different environments.

Knowledge-based support becomes context-sensitive as vocabulary about similar issues changes with different design situations, leading to different interpretations across companies (Ahmed & Storga, 2009). Apart from implicit reference in ‘issue’, no specific concept in EDIT makes explicit reference to information about R2S. Further work is needed to index knowledge where information about R2S is relevant for courses of action in the design process.

The deduction and analysis of inventions from patents claiming robustness resulted in strategies (Figure 3) incorporated in the robustness taxonomy (Jugulum & Frey, 2007), by focusing upon claims that corresponded to robust design terminology (Taguchi & Tsai, 1995). These were derived from analysing and classifying inventions according to the type of parameter (input, noise, control, and output) they aimed to change in justification of their robustness claims. The taxonomy is decomposed in *type-of* classes for uncoupled issues with a single working solution, and expresses strategies language better suited for control systems.

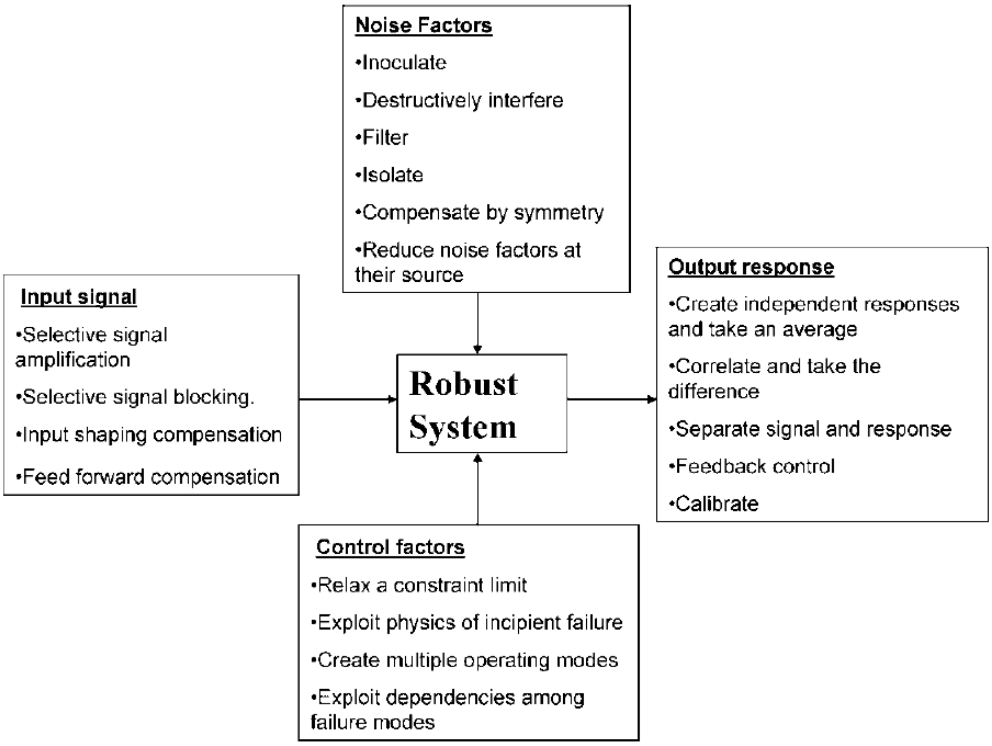

Figure 3 – Taxonomy of robustness strategies (Jugulum & Frey, 2007)

The relations between concepts such as ‘signal’ and ‘noise’ are not described beyond their depiction in the p-diagram. These are especially important in mechanical systems, as their working principles do not decouple signal from energy (Whitney, 1996). For instance, the storage capacity of a hard drive is directly influenced by the interdependence between design parameters such as accuracy of actuators, inertia of read/write arms and speed of the spindle (Whitney, Nevins, De Fazio, & Gustavson, 1994).

The use of signal flow language means that the concepts of signal and noise do not directly relate to the synthesis of mechanical properties in working principles (Matthiassen, 1997). Many examples by Jugulum and Frey demonstrating the robustness taxonomy emphasize hardware control systems: on the coolant pump example, there is no comment on the pitch system design and its effect on the coolant flow for implementing the control strategy.

2.2.2. Design models

In early design phases, models to codify information about design concepts are used in industry (Bonnema & Van Houten, 2006). From flow-based structures that decompose the design problem (Pahl & Beitz, 1996), to embodiment representations at different levels of detail (Andreasen, 1992), represent a set of attributes of the design, either by embodying a few attributes of the whole product or by concentrating on characteristics that represent quality issues (Thomke & Bell, 2001). This section focuses on models as guidance to the process of identifying quality issues.

Pahl and Beitz (1996) propose the modelling of product functions beginning, with a single overall declaration formulated as *verb-noun* pair, which is decomposed into a series of input/output transformations of energy, material and information flows. The theory of technical systems demonstrates the evolution from process to function and then to principles and embodiment (Hubka & Eder, 1992). However, the decomposition becomes more cumbersome as function structures become more complex, and is susceptible to different interpretations by different people.

This motivated the development of an approach intended as a standard, to allow further uses for technical functions (Stone & Wood, 2000). While all definitions strictly related to function are present and explicit, other relevant attributes such as operational requirements are absent from the function model; such missing constraints in functional relations are weak points in functional language. A knowledge repository about mechanical parts for individual working principles compensates for this problem in descriptions of working principles, but falls short of addressing the lack of information about the use context (Kurtoglu & Campbell, 2009).

Graphic models communicate the attributes and relations of means to obtain a function, representing technologies that carry physical transformations. Examples are: freehand sketches render embodiments of working principles (Hubka, Andreasen, & Eder, 1988); governing equations and laws present essential working parameters (Pahl & Beitz, 1996); and symbolic drawings present attributes of shape and scale determining how the function is implemented (Roth, 1994). Figure 4 shows examples of technology and working principles.

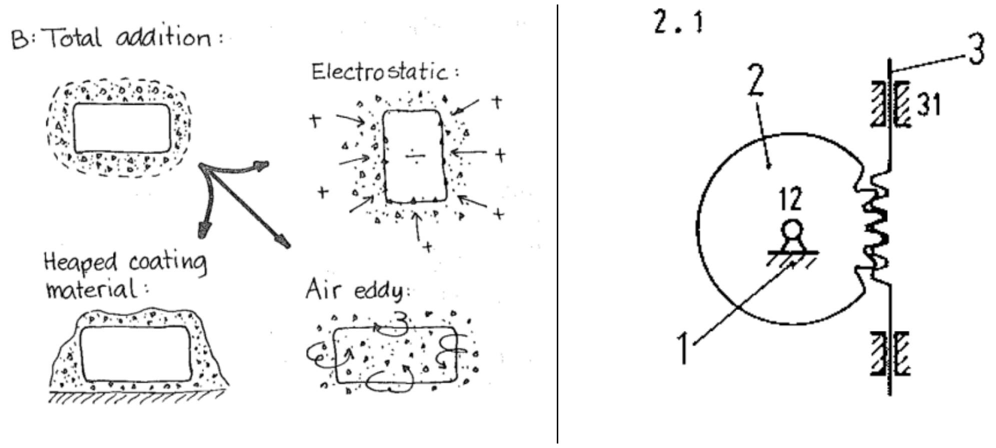

Figure 4 – Models of working principles: powder coating sketch (Hubka Andreasen & Eder, 1988); and, body diagram for rack-and-pinion mechanism (Roth, 1994)

Physical laws declare working parameters that are implicitly represented in sketches and symbolic drawings. Sketches such as the powder coating technologies shown above left are flexible to adding annotations such as text and graphic elements (Buur & Andreasen, 1989). Information about working parameters and their relations may be added at the discretion of the designers awareness of their relevance. Symbolic drawings such as the rack-and-pinion principle above right allow a restricted variety of standard symbols in annotations, which relate to information about R2S by geometry, shape and volume configuration attributes.

This trade-off needs to be appraised according to which representation carries more understandable information. Illustrations in patent descriptions represent attributes of an invention, whose utility is justified by functionality claims (Clausing & Frey, 2005). When robustness is claimed for mechanical inventions, cutaway drawings and body diagrams constitute the most frequent approach to displaying design attributes (Jugulum & Frey, 2007). This indicates that working principles declare design properties that relate to information about R2S attributes. Additional descriptions, such as governing equations and additional graphic elements, are useful as information about R2S, declaring how functional requirements are satisfied and maintained.

Freehand drawings such as used by Hubka and colleagues (1988) also render arrangement relations of components; annotated layouts for product architecture draw a correspondence between features and functions (Stone, 1997; Van Wie, 2002). Technical layouts represent component relations in position, arrangement and interfaces; cutaway drawings and assembly renderings from CAD models embody solution alternatives in dimension, scale, and position of their working principles (Baba & Nobeoka, 1998). Figure 5 shows examples of layout models for design concepts.

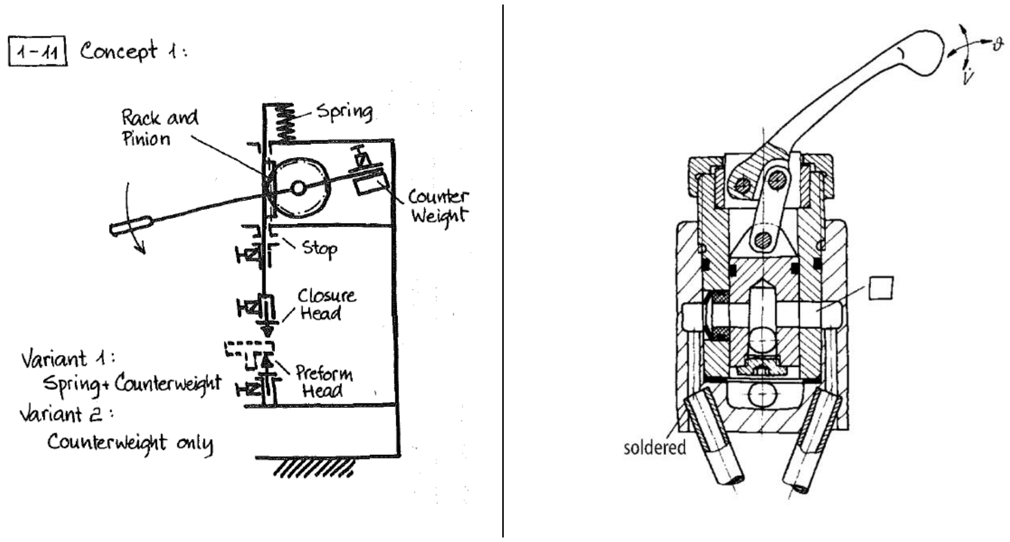

Figure 5 – Design concept models: sketch of rivet union tool (Hubka Andreasen & Eder, 1988), at left, and cutaway drawing of water mixing tap (Pahl, Beitz, Feldhusen, & Grote, 2007), at right

The sketch of the rivet union tool, shown in Figure 5 as an example, introduces how different working principles are arranged in a concept, but does not render dimensional or scale attributes. The illustration of the water mixing tap concept renders the format of interfaces, aiding the recognition of components such as flow selection interfaces for stable and effective selection of mixtures of cold and hot water. Relevant attributes of concepts are declared in both layout model examples, but information about R2S that relates to their dimensional, arrangement and mode of action attributes can only be recognized by trained observers.

For this reason, common models for mechatronic systems have been pursued to link between behaviour and quality attributes (Buur & Andreasen, 1989). Detailed models and working prototypes describe product concepts and of how they perform with richness of information (Ulrich & Eppinger, 2002). Geometry constructions of concepts in 3D CAD models can be translated to other models and representations to decrease the time between building and testing (Baba & Nobeoka, 1998). Rapid prototyping assists the verification of concepts by translating CAD files into physical models (Van de Velde, Van Dierdonck, & Clarysse, 2002).

Component block diagrams, depicted in Figure 6, are simpler models that support the clarification of design attributes: design principles (Stephenson, 1995); technical functions (Covino, Rodgers, Smith, & Clarkson, 2000); and mating/dynamic considerations (Smith, 2002). This requires part and assembly models for checking structure and interfaces with the use of knowledge about surface interaction attributes of components, with engineering judgment as criterion (Smith & Clarkson, 2005). The information about R2S that is used in this technique becomes complex; summarized forms fall short of guiding the evaluation of alternatives due to the loss of contextual information.

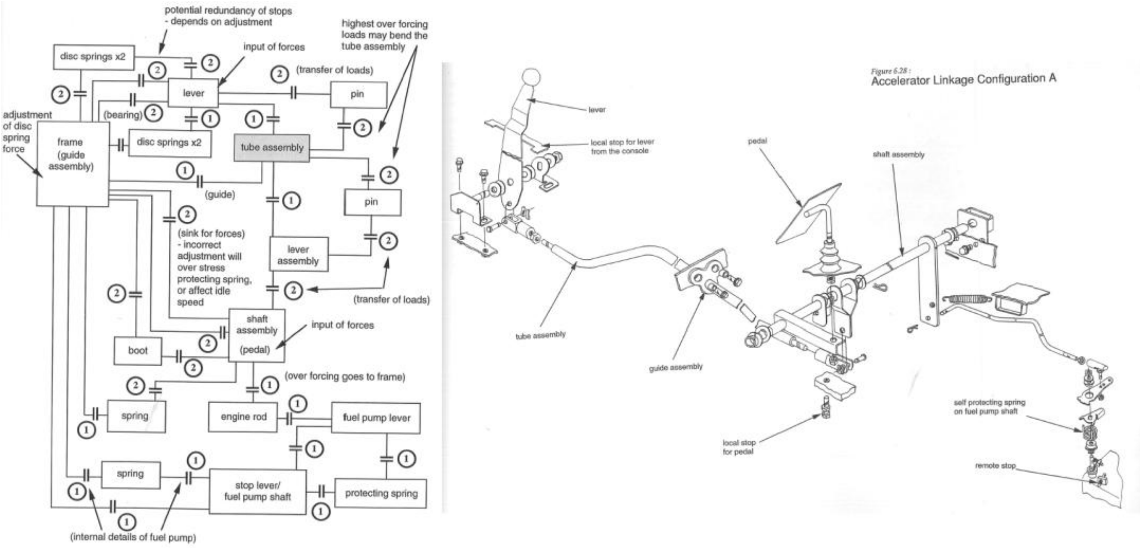

Figure 6 – Flow diagram and exploded perspective for the DFR method, from (Stephenson, 1995)

2.3. Knowledge management in design

This section first reviews mechanisms for reusing experience and knowledge in the design process, such as learning by doing (Von Hippel & Tyre, 1995). These constitute resources for identifying opportunities for improving the design and design strategies to realize and implement these; these determine the path to improve the design. This is followed by considerations about *design reuse* on how currently available designs can provide templates for the implementation of new designs (Clausing, 1998); these are intended to discuss the influences of design reuse towards meeting design requirements and the achievement of design goals.

2.3.1. Experience and knowledge reuse

The recognition of individual design situations within templates as identified by Von Hippel and Tyre (1995) elicits expert knowledge to identify problems, question their conditions, and engage in solving them. Learning and experience generate context-sensitive strategies that help to design improvements. The distance between producers and users of knowledge helps the identification of situations where available knowledge is used (Markus, 2001), which are also defined by the purpose to which knowledge is reused, and by the difficulties involved in this reuse. The distance between producers and users influences the frequency of knowledge reuse: the shorter this distance is, the more frequent is the reuse of knowledge.

Another factor in situations of reuse is the degree of codification required to interpret sets of vocabulary and tacit rules, i. e. across disciplines: the greater the distance to the producer, the more codification is needed. According to Markus (2001), difficulties of knowledge reuse do not relate to its applicability, but only to its interpretation and retrieval: shared work producers have difficulties in organizing knowledge for easy retrieval and sometimes fail to remember where it is accessible; expertise-seeking novices share neither the same vocabulary nor the trade of producers, which explains their difficulties in understanding the issues involved and identifying questions to ask. In design activities, knowledge reuse involves a certain degree of closeness between producers and users, as design work requires frequent use of knowledge. In engineering design, two approaches are used: adaptation and innovation, as displayed in Table 9.

In adaptation, there is a beneficial relationship between precedents and design projects: on the one hand, existing designs eligible for reuse allow variations of use and efficiency improvements (McMahon, 1994); on the other hand, reusable designs offer 'templates' that facilitate the generation of new content for ongoing design tasks. Designers refer to 'chunks' from past designs, used either to reconstruct characteristics of the intended product or within the ongoing design process (Eckert, Stacey, & Earl, 2005). There may be a lack of clarity about what past design is to be used and at what level; and a lack of criteria about constraints in the past design that affect its suitability.

Table 9 – Situations of knowledge reuse according to purpose: adaptation (Eckert, Stacey, & Earl, 2005) and innovation (Majrczak, Cooper, & Neece, 2004)

	Precedents	Application	Mechanism
Reuse for adaptation	**Inside the domain knowledge within the organization** Past knowledge to obtain shortcuts for attributes in the new application	**Incremental changes to ensure required attributes** Requires a significant degree of long-term attributes for ensuring reputation	**Past designs as adapted precedents** References to meet known criteria, and then embedded within the new solution
Reuse for innovation	**Outside the domain of practice in the organization** Foreign knowledge to close performance gaps or enable novel functionality	**Challenging vision to attain innovative attributes** Requires significant mission-critical attributes for ensuring to satisfy intended purpose	**Foreign designs as direct precedents** Significantly changed to meet new criteria and matured for the new solution

In innovation, there is a lack of past solutions within a particular application domain: teams need to diverge from usual knowledge to find a solution (Majrczak, Cooper, & Neece, 2004). This starts with the redefinition of the need for creating a challenging vision, giving incentive for the pursuit of a wider envelope of ideas. Here, significant gaps between current expertise and intended functionality drive the search for precedents outside the domain of the project. Majrczak and colleagues (2004) found that potential windfall profits within the organization provide incentive to search for new knowledge outside of the organization; the search for past designs is favoured by the belief on suitable solutions somewhere. In opposition to codified definitions of the design process (Ulrich & Eppinger, 2002; Sim & Duffy, 2003), problem-solving strategies are often tacitly assumed (Lawson, 2004).

Ongoing design tasks carry attributes analogous to those of past situations, triggering the use of specific prior knowledge to generate a solution; experts decode these when interpreting past experiences in the light of current problems, and select adequate strategies and criteria (Ball, Ormerod, & Morley, 2004). Expert knowledge in a certain field such as mechanism design can be summarized in design principles that orient for the definition of parametric relationships in component characteristics (French, 1992; Matthiassen, 1997). This can be further developed with the acquisition and use of expert knowledge, though modelling how experts tackle design issues (Ahmed & Wallace, 2004).

2.3.2. Design reuse

Experiments on analogical reasoning uncovered strategies with episodic references to demonstrate, evaluate, and take decisions about developing solutions. These are used to share ideas through analogical reasoning, but the qualification of 'what is relevant' to 'what situation' makes an issue for their proper use (Visser, 1995). Modes of change in design describe how reference designs can be selected and used according to whether functional requirements allow new uses i. e. can be adapted to a new context, or take advantage of technologies that yield potential gains in scale, efficiency or reputation in performance and R2S attributes (McMahon, 1994).

However, waste of resources is a consequence either from reference designs that cannot be adapted to new needs, or from design rework that introduces unexpected constraints. Hence, completely original designs only work for a single product and are difficult to adapt to a new problem (Clausing, 1998). Difficulties with design reuse were discovered to be due to the several obstacles related both to difficulties in overcoming constraints in product designs and to interaction problems between individuals in design departments (Busby, 1999).

Increased design reuse in engineering organizations is facilitated by the preservation of expert knowledge, and the increase of tolerance to past solutions in new problems (Busby, 1998). Besides employing verification and feedback for improving R2S attributes, set-based development uses past knowledge from records and expertise as controls for design reuse (Ward, Liker, Cristiano, & Sobek, 1995). Table 10 shows how the approach works on the variety of alternatives and their integration.

Table 10 – Control and reuse in set-based development, from (Sobek, Ward, & Liker, 1999)

Single alternatives	**Define feasible regions** Engineering checklist of records from tests and production about principles and ranges	**Look for intersections:** Designers look for intersections on common principles and ranges in subsystem interfaces
Sets of alternatives	**Impose minimum constraint:** Chief engineer takes responsibility for managing uncertainty across parameters through approval gates	**Narrow sets with increasing detail** Teams of different systems sift some of the alternatives that better fit the feasible parameter ranges
	Control	**Reuse**

Records created from testing and manufacturing procedures establish guidelines for design work; they define the context that alternatives need to meet in order to benefit from available manufacturing capability. This facilitates the design of interfaces for adjacent subsystems so that they fit together regardless of the concept adopted. In addition to the records, the chief engineer manages the evolution and reuse of alternatives to converge into the best possible compromise (Sobek, Ward, & Liker, 1999). Figure 7 shows how the process works with a Toyota supplier, and provides an example.

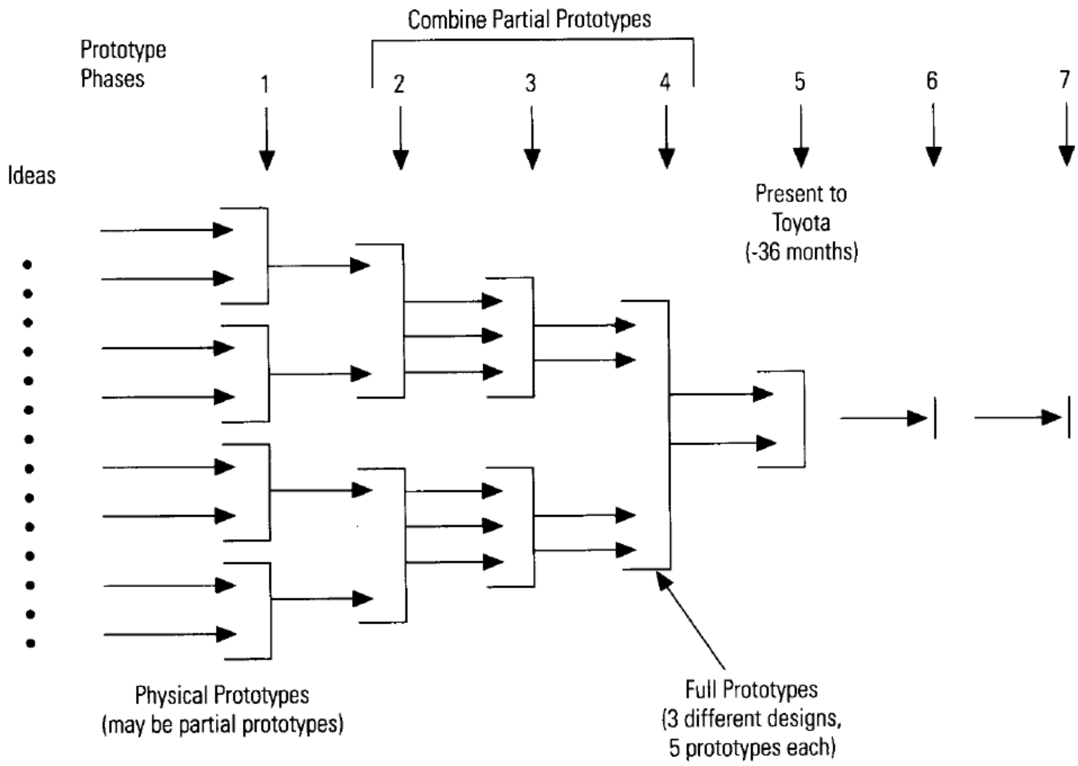

Figure 7 – Left: set-based development (Ward, Liker, Cristiano, & Sobek, 1995)

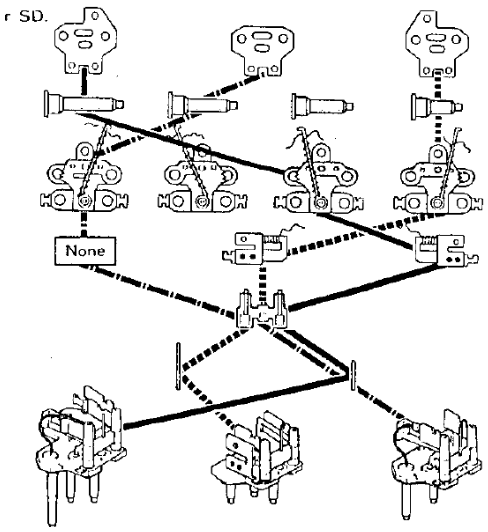

Figure 8 – Standard interfaces in modular architecture of panel meter (Whitney, 1993)

The process shown in Figure 7 is facilitated by extensive model-building around sets and by the standardization of component interfaces in modular architectures. Figure 8 shows how design teams can combine past designs into new ones, where new alternatives incorporate winning features of previous ones (Whitney, 1993). With the use of standardized interfaces, the developing design integrated within parameter ranges that are made to develop and converge through the design process.

2.4. Decision-making and feedback

This section begins with content about *decision-making, regarding the* judgment of and commitment to appropriate courses of action for developing attributes of solution alternatives (Dwarakanath & Wallace, 1995); the intention is to choose alternatives that favour the development of product attributes in downstream design tasks. Further on, content on *design feedback* calls attention to the treatment of design flaws (Gries, Gericke, & Blessing, 2005) affecting quality attributes; this is intended to describe current knowledge of how design feedback relates to the improvement of product design characteristics.

2.4.1. Decision-making

Decisions in problem-solving processes can be ambiguous and there are difficulties to anticipate the consequences from decisions, due to individuals' limited knowledge of the circumstances and effects of their choices make. Perceptual shifts on decisions often manifest in real engineering projects, as decisions in such a context are characterised by limited understanding of the intended outcome; this context is subject to the dynamics of organizational processes and the variety of conflicting interests involved (March, 1978).

Due to this limited knowledge, different perspectives on the object of choice cause changes in perceived probabilities, as individuals rely upon their prior knowledge to establish a first best guess about how the problem is to be solved (Einhorn & Hogarth, 1986). During this process, two situations may arise: first, that prior knowledge in individuals facilitates their awareness of what information to use, what to do and what outcomes to expect; and second, that individuals lack perceptions on how to proceed as they don't understand how the problem is structured (Schrader, Riggs, & Smith, 1993).

Appropriate communication channels and organizational resources are selected based upon that perception. Efficient problem-solving in decisions thus results from a match between the organizational context, the way problems are framed, and the resources available. To solve ambiguity, the controls and structure applied to the decision problem should be independent of the context of the problem; to solve uncertainty, the controls and structure should be specific: suitable solutions tend to come from resources already available in the organization (Schrader, Riggs, & Smith, 1993). However, this assumes design organizations as self-contained polls of resources and knowledge from which new knowledge cannot be generated.

Decisions in engineering design involve social and cognitive processes where many attempts to provide support are doomed to fail because of a lack of understanding of the dynamics of decision processes. Designers branch out hierarchical problem structures of partial issues to solve the decision problem; this is framed upon the definition of prior criteria, which evolve by refinement through the decision process and elicit the emergence of new factors understood as relevant to the decision problem (Dwarakanath & Wallace, 1995). The circumstances in the decision process are described in Table 11 regarding three classes: attitudes, constraints and classification.

Table 11 – Observations from decision-making, from (Dwarakanath & Wallace, 1995)

Attitudes	Constraints	Classification
Before making decisions, designers branch out issues and alternatives up to reaching satisfactory confidence	Designers tend to forget previously identified criteria and repeat earlier evaluations	Basic types of information used in decision-making can be grouped under issues, alternatives, criteria, arguments and decisions
Prior criteria evolve and new ones emerge during the design process	A few factors (criteria, issues) dominate the decision-making process	Two types of decision are observed upon alternatives: evaluate, and generate & evaluate

According to Dwarakanath and Wallace (1995), designers tend to forget criteria for decisions that were previously identified and repeat earlier evaluations in the decision process; the decision problem under discussion becomes more complex than the bounded rationality that individuals can handle. The organizational context may then induce pressure and constraints to prioritize a set of specific issues depending on the scope of the project and the object under consideration. With these factors constraining the decision-making process, the few issues that dominate the decision process result from individuals reprocessing the structure of issues and criteria to reduce ambiguity in the decision problem.

This implies a perspective upon the decision process as the generation of assumptions and preferences, and their exchange by participants in the decision task towards the convergence to a single set of commitments. The theory of dispositions is intended as a platform for predicting the impacts of design decisions. While this is done under a limited number of criteria, decisions impact upon all aspects of the design process; this is reflected in formulations that aim to describe these impacts so as to mitigate the lack of knowledge about directives and constraints in later tasks (Andreasen & Olesen, 1990).

This view by Andreasen and Olesen (1990) is supported by knowledge of downstream activities that serves as a basis for establishing targets in individual decisions. Choices about design properties in concept design constrain the freedom of later activities to implement significant variations in product architecture or part interfaces. These include constraints to detail design tasks such as the construction of prototypes and the design of manufacturing processes. Hence, dispositions carry on the flawed predictions of later impacts, where influences from design parameters are very often overlooked; later activities cannot fully grasp the issues they deal with. The inability to grasp influences on downstream activities makes it difficult to enforce directives and allows unintended constraints to arise during the design process (Flanagan, Eckert, & Clarkson, 2003).

This is reflected in the concept of information inadequacy as by Pich and colleagues (2002), from a lack of structural knowledge about problems, or from complex structures where knowledge of their effects is beyond current resources. To mitigate this, the management of dispositions involves the comparison between assumptions about project activities and their effect upon deliverables. Should this comparison indicate inadequate information about project tasks, two approaches may be used to address this: *to learn* about emerging factors and causal relationships; and *to select* factors and relationships on current options to realize their outcome (Pich, Loch, & De Meyer, 2002).

2.4.2. Design feedback

Design feedback creates awareness of the consequences of design activities, and works by eliciting courses of action from practitioners to deal with these (Busby, 1998). Engineers are expected to anticipate failure and avoid its occurrence in the solutions they develop and implement (Petroski, 1994). In spite of their skill, Petroski (1994) argues, engineers fail to take the lessons of past practice into account in their decisions or to understand their context as guidance to their reasoning. He uses reference case studies to communicate his views about principles of successful and unsuccessful judgment. Whether engineers verify their work and use engineering judgment determines the ability to anticipate impacts in R2S attributes.

The verification pattern is absent in the cases of failure, resulting in judgment errors in concepts that cannot perform or in structures that collapse upon failure; for instance, the Roman construction transporter failed to verify his concept before building the vehicle. These cases demonstrate that the lack of scrutiny against assumptions is a recipe for failure; for instance, the cantilever assumption by Galileo was not properly verified before it failed catastrophically in a construction. Failures only draw attention if they cause pain and then are forgotten some time after the damage has been done (Petroski, 1994).

For example, the girder bridge design in cast iron was successful in a series of projects up to its catastrophic failure on Stephenson's bridge, which neglected the weakness of cast iron to tension – the bridge structure created significant axial stresses. Engineers need to gather knowledge by verifying past designs and allow their verification by others; this influences the improvement of assumptions in current and future concepts (Petroski, 1994). However, there are signs that this dynamic is neglected in the workplace, at the same time that undue importance is given to specific outcomes over valid predictive methods; positive history on specific outcomes will lead to confirmation bias (Busby, 1998)a.

Feedback about R2S attributes is associated with design rework, and therefore seen as negative, is carried out intermittently, and only becomes compelling after a major failure. Inappropriate categorizations of product behaviour create obstacles to knowledge reuse amongst personnel who have different specialties. Problems with R2S are often seen as of secondary importance when compared with production and cost problems, but flaws are compensated by people engaging proactively in negotiation (Busby, 1998)a. Problems connected to feedback were classified into four categories, as shown in Table 12.

Table 12 – Examples of feedback errors in design, from (Busby, 1998)a

Planning at odds with past outcomes	Repeating errors that people find inexcusable	Unreliability in knowledge of outcomes	Predominance of negative feedback
Manifestation:			
Persistent surprises at rework, shared resources, disruption	Reusing problematic designs without knowing Accepting poorly-conceived systems	Inappropriate categorization of product behaviours	Belief that feedback consists entirely of complaints, criticism
Consequence:			
Reversion to shortcuts (risky but quick strategies)	Frustration among downstream functions	Decline in feedback giving/seeking behaviour	Loss of information Disincentive to refine product designs
Origins:			
Absence of distributional records of past outcomes	Failure to record error, rationale, assumptions Failure to reflect on error	Divergent assumptions across disciplines	Design evaluated by reference to error-free outcomes

Set-based development emphasizes proactive knowledge reuse about parameter ranges, as opposed to discrepancies from design flaws (Sobek, Ward, & Liker, 1999). Verification in this strategy takes place in two steps: during the generation of a variety of alternatives, and in the communication in sets to other teams. These verify, respectively: conflicts within a given functionality scope, then intersections between sets for robust integration. Feedback is carried out internally by looking for intersections, and externally by progressively narrowing the variety of alternatives. The use of these strategies is summarized in Table 13.

Table 13 – Verification and feedback in set-based development, from (Sobek, Ward, & Liker, 1999)

Single alternatives	**Explore trade-offs in alternatives:** Design teams generate several alternatives for individual subsystems	**Look for intersections:** Designers look for intersections on common principles and ranges in subsystem interfaces
Sets of alternatives	**Communicate sets of possibilities** Designers present sets of alternatives within feasible parameters	**Narrow sets with increasing detail** Teams of different systems sift some of the alternatives that better fit to feasible parameter ranges
	Verification	**Reuse**

Ranges of acceptable outcomes are verified and negotiated: if information needed is not available, development teams need to evolve design solutions clarifying structural and parametric relations in components and interfaces, and adjusting design characteristics against emerging properties that change desired attributes. (Terwiesch, Loch, & De Meyer, 2002).

2.5. Conclusions

Designers have yet to use a suitable language to apply their knowledge in dealing with information about R2S (Matthiassen, 1997). To this end, taxonomies cover several types of problems under 'umbrella' classifications derived from the consideration of a variety of practical situations (Ahmed 2005). These are composed of individual concepts that communicate information and are flexible enough for interpretation. This creates a common ground for design teamwork that can address issues in conceptual design.

Current R2S methods specify knowledge in different ways: estimating cause-effect relationships in system units; and eliciting heuristics and design principles to address issues with R2S. Their applicability to early phases depends on how the design information in early phases is linked to R2S attributes in system and product design. The review concluded that there are a few methods codifying information about R2S that provide application guidelines in design, manufacturing and operational contexts (Glossop, Ioannides, & Gould, 2005).

Design description requirements specified in the HAZOP standard (BS IEC 61882, 2001) demand a significant amount of data whose generation is not feasible by the concept design phase. The procedure for FMECA assumes a definitive principle solution is available, and the level of analysis is determined by experience (EN 60812, 2006). At early design, current methods for R2S are too cumbersome and do not guarantee the discovery of inconsistencies in system design and its integration.

Decision-making is of pivotal importance in regard to exploiting knowledge of the design process. The recognition of this in the engineering area has led to a consolidation of the characterizations of decision tasks, such as dispositions (Andreasen & Olesen, 1990). Development of this area leads to the identification of mechanisms and shortfalls in the decision process. The implications of a decision depend upon: uncertainty, which reflects a lack of knowledge about their values; and, ambiguity, which reflects a lack of knowledge about their relationships (Schrader, Riggs, & Smith, 1993).

The inherent ambiguity in conceptual design is mitigated by episodic references, which reflect an opportunistic character (Visser, 1995). Observations confirm this through the evolution of criteria, the generation of variations in alternatives, and the forgetting of prior information (Dwarakanath & Wallace, 1995). The problem with such statements is that there is no *single solution* to solve all problems that designers face. The best approach is to accept the uncertainty and try to navigate on through.

2.6. Summary

This chapter on the literature review described the research context and the fields of study involved in this project through the following sections: the introduction on the delimitations of the study, the assessment of models for design information; then the discussion of methods for R2S in terms of functional and scenario analyses; decisions and feedback regarding the issues in making and implementing commitments; and design and knowledge reuse are addressed on the sources of knowledge and their use in the design process. Conclusions are developed about the use of models in codifying information and how these influence the commitments throughout the design process.

The review of methods for risk and reliability reflected two approaches of interest in the codification and use of information about R2S: methods focusing on the qualification of product functions (functional analysis) and their influences on overall performance, and the methods focusing on the influences of product functions (scenario analysis) in the occurrence of an incident. Knowledge models are divided into taxonomies for organizing and indexing forms of knowledge and models for representing characteristics of design solutions, reflecting the progress in the use of information from strategies to tactical forms.

Knowledge reuse is understood to take place in two levels - adaptation and innovation - , being affected by the 'distance' between providers and users. The section on design and knowledge reuse focuses on the role of precedents and their use as knowledge in design activity: reuse is considered to take place from prior records and across alternatives; and precedents act as templates for communicating solutions or generating desired attributes. Decision-making and feedback are addressed regarding the shortcomings of decision-making and the strategies employed to deal with the problems that arise. This chapter concludes by summarising the implications of the issues to the research questions in Table 14:

Table 14 – Implications of literature review to research questions

Research questions		**→ Literature review**	
(1)	**(2)**	**(3)**	**(4)**
Need to assess information requirements from methods for R2S to verify the opportunity to taxonomies organizing information about R2S	**Current knowledge about decision-making and feedback does not consider implications to developing R2S attributes in early phases**	**Use of information is more or less well-defined in current methods, but does not fit concept design or platform rethought**	**Proposed strategy needs to codify information about R2S mitigating current of decision-making and feedback issues in early phases**

Chapter 3 - Research method

This research builds on current knowledge about the codification and use of information in early design phases. The research method structures procedures of scientific inquiry. This includes the employment of specific methodology for design research, as a basis for the planning and the evaluation of the research activity. The intricacies among stakeholders in design activity demonstrate the need to consider the influence of historical and social developments (Bucciarelli, 1994); this social-technical character in design is brought into view by considering the risks and experiences of catastrophic failure (Hales, 1993; Petroski, 1994). The following examples highlight the need for a strong research methodology:

- Prior contributions were held to make erroneous assumptions that did not reflect the reality of design practice (Maffin, 1998).
- Systematic methods neglect organizational constraints (e.g. quality of information, resources and management), which leads to scepticism (Frost, 1999).

Frost (1999) observes two mistakes in *design science* (Hubka & Eder, 1987; Beitz, 1994):

- Neglect of the role of experience and knowledge of practitioners in industry,
- Failure to address the negotiation of concrete designs in new applications, and,
- Use of terminology in prescriptive methods that is foreign to industrial practice.

Product development teams manifest a knee-jerk rejection to new methods, as designers would have to use something they were not involved in making (Andreasen & Hein, 1987; Boothroyd, Dewhurst, & Knight, 1994). This perception is due to the misinterpretation of abstractions by *problem-oriented* prescriptive methods, such as in systematic design and the theory of technical systems, against common *product-oriented* design practice outside of Germany (Wallace & Blessing, 2000). There was a lack of awareness of the formation and use of expert knowledge in prior systematic methods. The following criticisms apply to systematic methods (Frost, 1999):

- Tacit understanding about what works and what does not,
- Intimate knowledge of trade-offs and optimal states,
- Opportunistic and goal-oriented focus on the concrete product,
- Use of past and compatible designs to assure positive perceptions, and
- Interest in market constraints such as patents, regulations, and liability.

These points created discussion about whether engineering design has attained maturity, and about how it could better reflect the reality of practice (Cantamessa, 2003). Scientific rigour in engineering design research entails the need for coherent dialogue between apparently disparate views of the world in the natural and social sciences (Samuel & Lewis, 2001), and for empirical consistency regarding the implementation of approaches by means of a dialogue with industry.

3.1. The DRM framework

While engineering design gained relevance amongst an engaged community producing quality scientific output (Andreasen, 2001; Sheldon & Foxley, 2003), it lacks a common and articulate frame of thought in symbols, terminology, values and exemplars. Such needs create tensions within the design research community that need to be reconciled. The issues of concern include (Eckert, Clarkson, & Stacey, 2003):

- The pace of development,
- The need for quality and reliability,
- The necessity of shared meaning, and
- Openness to new interpretations.

Most results are presented in scientific publications only and rarely put into practice; until recently, there was little interest in their practical implementation (Cantamessa, 2001). Considering the view that design research should address practical issues, prior research methodologies focusing knowledge for its own sake could be useless (Reich, 1995). Shortcomings in the practical use of knowledge motivate the need for empirical inquiry and intervention for improvements. Hence, questions arise on how to improve the chances of producing a successful solution (Blessing & Chakrabarti, 2007):

- What do we mean by a successful product?
- How is a successful (or unsuccessful) product created? And
- How do we improve the chances of being successful?

These questions address the matter of relevance from research contributions: the community should engage with society in producing and disseminating knowledge (Papalambros, 2009). By the means of the questions above, DRM offers a supportive framework for scientific inquiry and dialogue with industry in design research. The theoretical framework in DRM in Table 15 provided a template for structuring and developing the research questions and activities that delivered new knowledge regarding the contribution from this study.

Table 15 – Stages in the Design Research Methodology (Blessing & Chakrabarti, 2007)

Stage	Focus	Object	Outcome	In this study
Research clarification	*Identification of metrics*	Indications and evidence supporting assumption	Goals of research	**Question (1), Papers I, II**
Descriptive study I	*Assessment of influences*	Understanding of situation and current shortcomings	Understanding about the context	**Question (2), Papers II, IV, V**
Prescriptive study	*Proposition of support*	Approaches to address or correct targeted factors	Support to practice	**Question (3), Papers V, VI**
Descriptive study II	*Validation of application*	Verification of the effectiveness to realise improvement	Evaluation of performance	**Question (4), Paper VI**

This research starts with research clarification from prior studies so as to plan the research effort. The first descriptive study (I) reviews current knowledge, complemented by a case study if information required is missing. This addresses the need for an empirical inquiry to direct the focus of improvement (Cantamessa, 2003). Then the prescriptive study involves the development of an approach to intervening in the practical setting, information-based support designed and realized within the project. A second descriptive study (II) is performed to investigate the impact of proposed support on realizing the intended improvement.

3.2. Research questions

This research aims to address the use of design information to declare attributes of robustness, reliability and safety (R2S) that have a positive influence in early design phases. Its object is <u>*information about R2S as relations between design characteristics and R2S attributes*</u> addressing needs from the operational lifecycle. These relations are defined in the design in degrees of detail level and structure, which determine a thought process where designers describe characteristics of the design and assess their implications to R2S attributes.

The aspects outlined by the literature review are in fact manifested in an inter-related manner. While design departments acquired long-term experience by having to deal with these issues, there is insufficient knowledge to evolve explicit understanding about these problems. This hinders the discovery of opportunities to improve the way design issues on R2S attributes are treated in practice. Research strategies are shown in Table 16 according to how they deal with different aspects of phenomena: what knowledge can be attained, the requirement for control and the timeliness against the phenomena. Hence, the combination of research issues motivates the use of case studies as a strategic approach for this research.

Table 16 – Research strategies based on types of questions (Yin, 1989)

Strategy	Form of research questions	Requires control over events?	Contemporary events?
Experiment	How, why	Yes	Yes
Survey	All 5W2H questions	No	Yes
Archival analysis	All 5W2H questions	No	Yes/No
History	How, why	No	No
Case study	***How, why***	***No***	***Yes***

5W2H: Who, What, When, Where, Why, How, How much

In early design phases, people process information on design alternatives to identify shortcomings and benefits to R2S attributes. As events in this context are characterized by uncertain outcomes and ambiguous development, the challenges of using, codifying and declaring information about R2S for use in early design phases inform the empirical approach in this project as:

- Information cannot be confined within specific events,
- Issues are not completely understood for the definition of controls,
- Events are too intricate to be explained by historical archives only.

The challenges of using information about R2S in early stages are not only defined by the knowledge areas; they are also influenced by the context of how such knowledge is used and processed to carry out early design tasks within a project. These challenges motivate the selection of case studies as a research method, which affords the exploration of empirical evidence to understand practical situations and address their improvement (Yin, 1989). Case studies are best suited to this project for two reasons:

- There is no thorough understanding of the research object, and
- Its circumstances and relationships change over time and place.

For the use of case studies, there is need to decompose the research object in manageable parts: the need is first addressed by an overall question stating the strategic knowledge being pursued; as design tasks in early phases were better understood, specific research questions were established. Table 17 shows the approach to research questions in this study, derived from DRM.

Table 17 – Structure of research approach: decomposition into specific sub-questions

Question of this research: How to codify and declare information about R2S to influence positively the solution of problems in early phases of the design process?			
Research questions			
(1) **What information about product design do current methods for R2S need to generate information about R2S in a product?**	**(2)** **How does information about R2S from concept design influence practice to improve R2S on solution alternatives?**	**(3)** **How to model information about R2S in solution alternatives for methods that elicit practice to improve R2S during concept design?**	**(4)** **How does the proposed model of information about R2S support practice to improve R2S during concept design from a method for R2S?**
Sub-questions			
(1a) Which design information is accessible during early phases? **→Paper I**	(2a) When are methods for R2S carried out during early design phases? **→ Paper III**	(3a) How should design information be used to declare information about R2S? **→ Paper V**	(4a) Does the information about R2S help address solution alternatives? **→ Paper VI**
(1b) Which design information is sufficient for using methods to R2S? **→ Paper II**	(2b) Which shortcomings appear in current use of information about R2S? **→ Paper IV**	(3b) What arrangement helps to identify/retrieve information about R2S? **→ Paper VI**	(4b) Does information about R2S help elicit improvements to R2S? **→ Paper VI**
	(2c) Which elements are responsible for the shortcomings? **→ Paper V**		

Research question (1) focuses on coding and processing information about R2S during early design phases. This is addressed in Paper I and Paper II, which discuss the feasibility of current methods with information from early design phases and the way this information is coded for use with current R2S methods, respectively. These contributions define the current approach of coding information about R2S through the design process: the availability of information influences the feasibility of current methods, whose complexity demands prior knowledge and significant experience of the product.

Research question (2) addresses how design information about R2S is codified. This question is addressed in Papers III, IV and partially in V, which discuss the influence of current methods of providing information on deciding between alternatives, concerns about with decision-making and knowledge reuse in early design stages, and the impacts on development strategy of the current use of design information. Actual practice of current methods fails to provide feedback for improvements and thus impairs the effectiveness of design decisions in eliminating shortcomings in R2S attributes.

Research question (3) focuses on support for using information about R2S in early design phases. These comprise the assessment of conditions and the design of the approach to developing the tool: Paper V examines the conditions of use and communication of design information in early design phases, and paper VI assesses requirements for developing support and proposes a user interface to address information about R2S in solution alternatives. The strategic conditions of early design phases include a control-convergence process that needs formalized support to decision and feedback, which is developed by communicating prior cases of failure and success in early phases.

Research question (4) concentrates on the verification of potential improvements to the use of information about R2S for improving the convergence of design solutions, thereby validating the proposal in this study. The verification of results from the proposed support is carried out by means of a design task simulation: paper VI evaluates the performance of designers taking decisions with the support of the interface communicating cases of failure and success in solution alternatives, and how designers build improvements upon the remaining issues in the alternatives that were chosen.

3.3. Research stages and case studies

To gain knowledge about the possibilities for codification and use of information about R2S in early design phases, this research was implemented on the basis of the DRM methodology. Starting from theoretical knowledge in literature review, the acquisition of knowledge for this research engages with practice environments. To address the research questions stated in Table 17, this study was developed through the procurement of knowledge from different sources. The following objectives guided the execution of this research:

- A *literature review* was carried out, considering the fields of study involved,
- A *pilot case* study was performed with current R2S methods to understand their information requirements,
- An *industrial case* study was done to understand industrial practice in addressing information about R2S in early phases, and
- A *proof-of-concept* test was performed to propose and test a solution for codifying and using information about R2S in early phases.

Literature review was performed throughout the study, serving as a preliminary criterion for evaluation; its content is used as background knowledge for establishing assumptions, comparing characteristics among different approaches, and assessing the results obtained.

The pilot case was executed to clarify problems on how current methods for R2S required information about product design, and on how they codified information about R2S. The industrial case was performed as an empirical investigation within the industrial setting, to assess situations of the generation and use of information about R2S from early design alternatives, and extract its results as a basis for developing an approach to codify early design information. The proof-of-concept test was performed to assess the suitability of the proposed prescriptive approach to circumstances of the industrial setting by a simulated experiment.

Table 18 shows the correspondence of research streams to stages in the DRM framework.

Table 18 – Research implementation: approaches used in methodology stages

Research clarification	Descriptive study I	Prescriptive study	Descriptive study II
Literature review	Pilot case	Industrial case	Industrial case
Pilot case	Industrial case	Literature review	Proof-of-concept
			Literature review

A literature review was performed with two main purposes: first, to build up a theoretical basis supporting research; and second, to discuss the currently available prescriptions specifically aimed at early phases, with focus on R2S attributes. This was used throughout the project: the review followed theories, models and cases that consider R2S attributes in different types of product and design approaches; the discussion followed similar propositions establishing a framework of comparison in the thesis.

The empirical approach employed in this project comprises of two case studies: a pilot case and an industrial case. The designs analysed for the two case studies were a washing machine and an insulin injection pen. Both are carried out as exploratory case studies: the pilot case aims to clarify the research problem in regard to the availability of information and the way it is processed into coding in the current methods; and the industrial case consists of a full descriptive study of the use of current methods in early design phases and its impact on development strategy within the industrial context. Pilot case and industrial case are different due to the need to understand different perspectives on the research object.

- The pilot case seeks to understand the requirements of design information from current methods with a view to their codification of information about R2S, and
- The industrial case focuses the characteristics of the practical use of current methods and on their influence on the improvement of R2S attributes in early design phases.

The *pilot case* study was carried out as a 'simulation of practice' to clarify the use of information about R2S (research clarification) and focussed on the identification of risks derived from design issues. This consisted of using R2S methods with information on the working principles of an existing washing machine, aiming at the variety and the level of detail in information required by current R2S methods. The result of this exercise consists of an assessment of the information requirements of R2S methods, which are considered against the needs/availabilities of information in early design phases.

The *industrial case* study is an empirical inquiry into the use of information about R2S in early design phase, performed to assess the use of methods for R2S in industry and what the issues are that prevent the effective use of information about R2S. After 10 months of extensive data collection, the activity followed 36 months of an actual development project of a novel insulin injection pen. It consisted of a longitudinal and retrospective study, which was carried out in collaboration with a company that produces medical devices. This study identified the problems in using information about R2S in early phases, and proposed a means of supporting the use of information about R2S to review design alternatives.

Theoretical sampling (Eisenhardt, 1989) was carried out to select the case units. These were chosen by their relevance as a common situation of using R2S methods (pilot case), and as a reference situation for information about R2S in early phases (industrial case).

The *washing machine* was chosen as a unit for the pilot case because it was readily available for analysis. Its distinct functional modules simplified the use of methods for R2S with focus on the system integration aspects of known components. The understanding of its functions and performance was a basis for assembling the analysis. The structural characteristics and working principles of the washing machine serve to understand current R2S methods and their use of design information.

The *insulin pen* turned out to be a more complex case due to the originality of its design and the criticality of its requirement. It involved several design alternatives where current technology was rethought to enhance its functionality while adhering to strong R2S requirements. The insulin pen was analysed by its working principles and the solution alternatives, regarding the mechanism for setting and driving the dose for delivery of medicine. The characteristics of practice and knowledge domain in the development of the insulin pen serve as a case to identify current practices of information about R2S in early design phases. Table 19 describes product design characteristics in the case studies.

Table 19 - Characterization of product designs in case studies

Product design characteristics	Pilot case: washing machine	Industrial case Insulin injection pen
Novelty	Existing design	Original design
System architecture	Separate modules within a containing structure	Superposed, integrated assembly in tight packaging
Design focus	Integration of functions, optimization of system components	Development of working principles and their integration
Product scale	Machine, human body	Mechanism, grabbed by hand
Sample design	As manufactured and available for sale	As design alternatives for evaluation and testing
Role for case study	Common example of product design as access to knowledge on R2S methods	Reference example of design process as model for practice on R2S attributes

Considering the information in the table shown above, the investigation of the case with the insulin pen is performed with a significant focus upon design practice for R2S attributes in concept and technology development. This contrasts with the pilot case for the washing machine, which started by evaluating the integration of a common product as a basis for becoming familiar with R2S methods. The pilot case worked to establish research criteria, pointing to the need to further investigate the complexity of current methods for R2S attributes in early stages; the industrial case was conducted to address this aim.

The case study approaches were selected to understand information about R2S. The practices analysed were the use of R2S methods regarding the operation of a washing machine, and the practice for developing solution alternatives in the industrial context from information generated with current R2S methods. The *pilot case* was carried out on the need to understand the use of current R2S methods for information about R2S on a current design; and, the *industrial case* was executed to understand the influence of information about R2S on early design practice for implementing working principles. This is the second layer of theoretical sampling (Eisenhardt, 1989) applying to the variety of R2S methods.

Case units were chosen, considering both the R2S methods with widest application in the pilot case and the framework of methods and practice most representative for addressing requirements to R2S in products with significant risks to life.

The *pilot case* was carried out with focus on the use of current methods for R2S, with available design information describing its working principles. It focuses the use of R2S methods from available design information, and characterizes functions and working principles from a manufactured unit of the washing machine. This determines the approach of carrying out the pilot case as simulating a risk identification procedure (Wang, 1994) using R2S methods supported by use and service information. Hence, its R2S issues relate to the integrity of components, in order to avoid unintended projections of energy.

The pilot case then focuses on a single task in order to make a comparison between known methods for R2S in a single evaluation, regarding their information requirements as characteristic of a current design; the industrial takes an interest in the process of developing R2S attributes, which motivates a longitudinal study to assess the impacts of cumulative evaluations upon decisions and design feedback. There, R2S issues focus potential effects of incorrect movement of components during the delivery of medicine in interaction with the human body, such as physical and toxic injuries.

The *industrial case* is executed with focus on the influences of current R2S methods and their codification into determining how designers interpreted information on working principles and committed to given solution alternatives. The purpose of the industrial case is to assess the influence of current codifications of information about R2S on criteria for improving R2S in early phases. This determined the approach of the industrial case as a longitudinal study (Hales, 1993) supported by project documentation and designers' accounts about methods for R2S, issues on the mechanism design, and the measures taken on solution alternatives. The organizational characteristics determined the effect from relationships between resources, task allocation and knowledge aggregation into the context of investigation.

The *pilot case* was carried out in the academic environment and aimed to clarify the context of this research. This determined the restriction of its scope to engineering design descriptions and domain knowledge free from organizational considerations. The *industrial case* was undertaken by the researcher in collaboration with a company that produces the insulin pen, to understand the research object in the industrial context. The longitudinal character of the study was intended to help diagnose the influences of different detail levels on the design and evaluation of alternatives into the formation of choice arguments to select alternatives.

Table 20 describes the characteristics related to the case approach that determined the way research methods were used.

Table 20 - Characterization of current methods and research within case studies

Case approach characteristics	Pilot case: washing machine	Industrial case Insulin injection pen
Researcher	Performer	Observer
R2S issues	Component integrity, energy projection	Component movement, physical and toxic injuries
Execution	Simulated task, action-research risk identification	Actual project, longitudinal and retrospective study
Description focus	Study of criteria, without prescription or validation	Study of situation, with prescriptive model and validation test
Engineering domains	Fluid dynamics, structure analysis, mechanical vibration, control	Mechanism design, component tribology, mechatronics
Use of information about R2S	Several methods in single task to characterize current design	Practice in several tasks to develop alternatives and solution principle

The mutual influences of methods and practice are also determined by the domain experience of the engineers involved in the project; their particular understanding of why choices were made is informed by their tacit understanding of designs.

3.4. Data collection

The selection of multiple sources for inquiry improves the reliability of research findings from case studies (Yin, 1989). The nature of R2S methods, namely that they rely on several sources of information, imposes the need for diverse of data sources in this research. Different types of information carry specific aspects of how information about R2S is collected, codified and used for supporting the improvement of R2S attributes in design solutions. The study was organized in different case studies addressing a structure of research questions which benefits from the diversity of sources. To obtain knowledge of the use of information about R2S, four approaches to data collection were used:

- Document analyses were used to collect evidence about theories or documented facts through case studies that indicate or explain relevant issues in this research.
- Reverse engineering was used to analyse the constitution of the products in the pilot and industrial cases so as to identify system functions and their working principles.
- Analysis and modelling involved using information from reverse engineering and representing systems and components of the products with design models. And
- Interviews and workshops were used to collect views and insight from designers about how documented facts occurred or could be treated.

The first two data collection approaches were used to search for and extract the data that were relevant for the cases. Document analyses were used, as methods for R2S rely extensively on documentation about sources of information; these also supported the implications from information about R2S for decisions and design feedback in the industrial project. The other two approaches were used to process the data into common criteria and validate their occurrence throughout the contexts of each case.

Document analyses interpret explicit knowledge that is acquired either from public references or from corporate project databases. They create a detailed trail of information from tasks within the scope of the design process. However, they require a significant amount of work to decode the links and influences between dependent issues. Issues can only be explored one at a time, and several iterations are necessary to reach a consolidate network of factors.

Reverse engineering is used in the design process to make comparisons and generate improvements based upon a single set of logical criteria. The approach yields understanding of how performances of different products are determined by similarities and differences in their designs. They require a significant amount of work to interpret solution characteristics according to criteria, as they require either planned experimentations or thorough tear-downs of available products.

Observations showed how design tasks were executed and allowed the identification of actions by individual participants that influence the problem of research. These show how issues are tackled by designers in real time, exposing the strategies employed and revealing the reasons why they are used. However, a significant workload is entailed when following the actions of several participants, which become cumbersome to identify. This limitation requires clear judgment about which tasks to follow.

Table 21 shows the use of data collection methods through the research stages.

Table 21 – Use of data collection approaches in research

Literature review	Pilot case	Industrial case	Proof-of-concept
Document analyses			
Theoretical basis about technical risk and systematic methods	Documents about use and maintenance of existing washing machine	Documents for developing insulin injection pen: tests, methods and milestones	Documentation from workshop about design decisions and feedback
Reverse engineering			
State-of-the-art on approaches to system analysis and redesign	Disassembly and system analysis of a manufactured washing machine	Information from CAD assemblies and physical prototypes of design alternatives	Comparison between solutions from workshop and those from later stages of original project
Observations			
		Two observations of product risk management meetings joining up HAZOP and FTA	Video from workshop verifying the approach for decision and feedback
Interviews and workshops			
		Five interviews with team members, followed by one workshop about decisions on alternatives	Two interviews on user interface and scenarios of use; questions after the decision workshop

Interviews and workshops are useful for identifying personal views and underlying issues on the object of research that could not be acquired from documentation. These are widely adopted to obtain first-hand insight about the perceptions, motivations and decisions carried by designers in their activity. Circumstances of time and individual opportunity create the need for objectivity. The perceptions of interviewees, along with those of the researcher, tend to induce bias towards a given finding or solution.

Multiple data sources such as those used here afford the ability to test and substantiate the constructs found throughout the research (Eisenhardt, 1989). These sources act as internal cross-verification devices within the case studies, which creates the mechanism for this substantiation and helps convergence onto a coherent set of findings.

3.5. Data analysis

This research explores about the relations by which R2S methods declare information about R2S and elicit suitable mechanisms for design improvement in early phases. Data analysis approaches filter relevant information from data in empirical investigations. This process involves either the matching of data to existing constructs or the creation of new constructs carried by examples and thereby semantically tested. Table 22 shows the approaches used throughout the case studies.

Table 22 – Use of data analysis approaches in this research

Literature review	Pilot case	Industrial case	Proof-of-concept
Analysis and modelling			
Theoretical basis and state-of-the-art about systematic methods and engineering knowledge	Functional decomposition from product disassembly and illustrations, followed by use of R2S methods	Detailed system decomposition of design alternatives, analysis of working principles	Information and user interface design with feedback from specialists and engineers in industry
Codes from literature			
Definitions of R2S attributes and design characteristics in engineering knowledge	Organization of descriptions of systems and components of the washing machine	Organization of R2S issues and related information about the injection device during its design	Use of information types to separate aspects of R2S incidents on the injection device
Codes from documentation			
Results from articles evaluating the use of design theories in simulation or practice exercises	Use of information about design characteristics and R2S issues on the washing machine	Use of information on design characteristics and incidents about R2S issues with the injection device	Verification of the use of the proposed approach carried out by participants in workshop
Codes from observed events			
		Verification of R2S issues sampled from project documents and their influence on the outcome of the project	Verification of information use and its outcome when the proposed approach was used by designers

Analysis and modelling were used to communicate the characteristics of product designs and of information about R2S that was being processed and used. Models entail syntactic and semantic rules (Tjalve, Andreasen, & Schmidt, 1981; Roozenburg & Cross, 1991) that clarify and/or delineate specific attributes of the product or the process having a significant role in the research problem. This is achieved by identifying information units, the links between them, and the objects they characterize; these sets of syntax and semantic rules are used to represent the object, and identify issues that constitute information about R2S.

Codes and models *from literature* (top-down approach) were used when the design content of a research task could be interpreted with reasonable accuracy with existing knowledge. This was used to interpret instantiations of product designs into constructs that represent generic design characteristics. While this compares to the use of systematic design models for the ontology of generic design activities (Sim & Duffy, 2003), our purpose was to identify aspects of design information that could be measured qualitatively.

Codes from *documented records* (bottom-up approach) were used when the design content carried by data in a research task could not be described with current references. This compares to knowledge and design information used by engineers that is inductively inferred from documentation (Court, 1998; Court, Ullman, & Culley, 1998), and to categories and types of content in engineering email (Wasiak, 2010) in coding schemes. This research reproduces more closely inductive inferences from documentation (Court, 1998) and from interview transcripts (Busby, 1999) to verify aspects of information about R2S from documentation in both case studies.

Codes from *observed events* were used to track design activities to the matters of interest in this research. As executed with the former type, this research employs a directly inductive approach, where codes are first given examples and then assigned to findings (Busby, 1999). This approach can be compared to verbal analysis for extracting relevant information from interviews and group meetings (Chi, De Leeuw, Chiu, & LaVancher, 1994; Chi, 1997). A similar approach was used in this research to identify information about R2S declared and addressed by designers in group tasks.

Existing codes afford readily understandable interpretations of the research context as they are based on commonly accepted knowledge in a given research field. However, they do not cover all situations of ongoing research. Codes from data describe patterns of facts that introduce new conditions to understanding design processes. Design issues can be better tracked using codes from data, to find specific uses of information about R2S.

3.6. Conclusion

This chapter described the research approach of this project in four different sections: the introduction on theoretical approaches followed by the methodological basis justifying the approach to the research problem; research strategy defining the research object and statements in form of research questions and sub-questions; research procedure characterizing the streams of content and the empirical investigation through case studies; and, empirical data showed considerations about data collection and analyses that were performed through case studies.

This chapter concludes their objectives by discussing the elements that define the methodological basis, strategy and procedure that were carried out for completing this research. This chapter resulted in the following directions to research questions, as shown in Table 23:

Table 23 – Directions to research questions from the research method

Research questions		→ Methodology guidelines	
(1)	**(2)**	**(3)**	**(4)**
Need to assess information requirement:	**Consider implications to develop R2S attributes:**	**Use of information does not fit concept design:**	**Proposed strategy needs to mitigate current issues:**
Do a pilot case study focusing the use of current R2S methods with earl design models	**Perform an industrial case study regarding R2S attributes through concept design**	**Take the findings from the industrial case to develop a codification approach to R2S**	***Need to perform a proof-of-concept test simulating the use of the tool by practitioners***
→ Clarify criteria	***→ Describe situation***	***→ Propose intervention***	***→ Make preliminary test***

Interpretations of the product draw support from *problem-oriented* approaches that originated from accumulated experience in mechanical engineering and remain relevant (Hubka & Eder, 1992; Pahl & Beitz, 1996). Further on, this research follows the structure and understanding accumulated within a Danish model of understanding products at several levels, from need to component, as aids to getting things done (Tjalve, 1979; Andreasen, 1992; Andreasen, 2011).

Interpretations of product development are guided by curiosity in the US about successful product design (Hauser & Clausing, 1988; Petroski, 1994; Sobek, 1996), as well as by the British tradition of empirical research about issues on engineering design practice and knowledge needed to support the activity (French, 1992; Hales, 1993; Busby, 1998). All these are influenced by the frame of thought typical of formation and practice in natural sciences, particularly in mechanical engineering. These influences instil a pragmatic outlook to the topic of this research, while trying to intervene in the use of experience by practitioners.

The interpretations made here are also influenced by the selected research methodology (Blessing & Chakrabarti, 2002). Hence, the choices hereby presented aim at *models* for creating a baseline for understanding and intervening in the use of R2S information in early design. Literature review prior to the studies aimed to acquire understanding about this and led to goals being refined during the research. The models provide a basis for further efforts and greater achievement, as they make rationalistic sense on mapping the use of information for R2S in early design phases.

In this approach, the pilot case did not involve interviews, as the researcher himself assumed responsibility for learning the issues with R2S methods; the descriptive part of the industrial case involves interviews as objects of cross-verification against the data characterising solution alternatives found in documentation. The influences from views and intents of designers were not examined, as this was out of scope for this research.

Chapter 4 - Results

This chapter presents a summary of the central ideas presented in the articles together with the findings that address the research questions. The purpose is to summarise the core views and findings of this research, as current methods focusing upon R2S attributes are too complicated for effective use in early design phases. Table 24 considers the levels on which the codification of robustness, reliability and safety is seen to influence the design process from the perspective of the thesis:

Table 24 – Findings about the codification of product attributes towards the design process

Stages →	Research clarification	Descriptive study I	Prescriptive study	Descriptive study II
Codification of information about R2S	Papers I-II Requirements and sources of information		Paper VI Development of the approach supporting decision-feedback in early design phases	Paper VI Verification of the tool in exposure to expert practitioners
Practical use of R2S methods in design	Paper II Acquisition and use of sources of information	Papers III-IV Problems in design decisions and reuse of rationale as feedback	Papers V-VI Requirements and conditions for the use of early design information	Paper VI Verification of the tool in use by practitioners in simulated task
Consequences to design strategy		Paper V Consequences from decision-feedback problems to design process		Discussion Assessment of validity against other contributions and expert judgment
Research questions →	**What information about product design do current methods for R2S need to generate information about R2S in a product?**	**How does information about R2S from concept design influence practice to improve R2S on solution alternatives?**	**How to model information about R2S in alternatives for methods that elicit practice to improve R2S during concept design?**	**How does the proposed model of information about R2S elicit practice to improve R2S during concept design?**

The findings are organized around the research questions. The table above exhibits different levels of the problem related to stages of research and research questions. Each research question is discussed in this chapter through an overview of the levels from the table above, with detailed findings that are accessible in the papers appended. Partial contributions in individual papers address each research question; findings are described in response to the research questions, motivated by the need to address R2S attributes in early design phases.

4.1. Summary of papers

4.1.1. Paper I

Co-writers:	Marini, Vinicius K; Restrepo, J.; Ahmed-Kristensen, S.
Title:	**Evaluation of information requirements of reliability methods in engineering design**
Destination:	International Design Conference, DESIGN 2010, University of Zagreb and The Design Society (published)
Target Audience:	Researchers and advanced practitioners in Engineering Design and Product Development (conference presentation)
Motivation for paper:	Quantitative methods require a significant amount of data, and qualitative methods require design expertise. There is a need to unfold knowledge required by current R2S methods against the information which is available in early design phases such as concept design.
Research stage	Design Research Methodology: Research clarification: Criteria
Research approach	Action-research: Own use of methods with information acquired from reverse-engineering and modelling a manufactured product with models from early design phases
Summary of findings	Information in the models of the manufactured product (a washing machine) , representing different design phases, was gathered and then traced to individual types of queries in current R2S methods. A taxonomy of attributes specific to R2S was proposed by evolving the EDIT taxonomy to incorporate information about the behaviour of the product. Information about the product was then related to queries in current R2S methods regarding the design phases where it was available from the models used in the study. Early design models helped define the scope of evaluation and the elements being analysed, whereas relationships required to proceed with current methods could only be found in embodiment and detailed design models.
Contribution to thesis	The paper contributes to the thesis by identifying the difficulties to use current R2S methods in early design phases – as it is not possible to complete their queries – and directs further research efforts to identifying other possible ways in which R2S attributes could be treated in industrial practice of early design phases.

4.1.2. Paper II

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**Information requirements of current methods for robustness, reliability and safety during early design phases**
Destination:	Quality and Reliability Engineering International, Wiley, ISSN 1099-1638 (submitted)
Target Audience:	Researchers and advanced practitioners in Quality and Reliability Engineering for Product Design (journal article)
Motivation for paper:	Industrial practice involves the use of current R2S methods only when a consolidate principle solution is engineered, modelled and approved. There is interest in understanding how far they can be applied during early design phases, in order to ascertain their role during the design process.
Research stage	Design Research Methodology: Research clarification: Criteria
Research approach	Action-research: Applying R2S methods with information acquired from reverse-engineering and modelling a manufactured product with models from early design phases.
Summary of findings	Information about issues, failure modes and events in the behaviour of the product was obtained through more complex descriptions. Information about components was explicit, whereas information about issues was suggested by working principles, and information about functions remained implicit in relationships between different sources. Existing information from records of use of similar products about working principles and their behaviour helped to identify intended operating states and issues that precipitate deviations from these. This was found to be characteristic in adaptive designs by reliance on previous knowledge and experience, but not possible with innovative product designs that determine the execution of concept design in industry.
Contribution to thesis	The paper contributes to the thesis by confirming the feasibility of the partial use of current R2S methods in early design phases, and clarifying the design situations (adaptive, innovative) where relevant information is absent. This paper contributes to the thesis in relation to the development of ways of revealing mechanisms of failure with working principles during early design phases.

4.1.3. Paper III

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S., Restrepo, J.
Title:	**Influence of design evaluations on decision-making and feedback during concept development**
Destination:	International Conference on Engineering Design, ICED 11 Technical University of Denmark, The Design Society (published)
Target Audience:	Researchers and advanced practitioners in Engineering Design and Product Development (conference presentation)
Motivation for paper:	If methods for R2S require a significant amount of data and design expertise, then it is necessary to know how designers actually address this challenge. This motivates an investigation of industrial practice regarding how design characteristics with influence on R2S attributes are considered during early design phases.
Research stage	Design Research Methodology: Descriptive Study: Influencing factors
Research approach	Longitudinal study (36 months): Document analyses, reverse engineering and interviews to collect information from an industrial project to develop the principle solution for an insulin injection pen.
Summary of findings	Placement and use of evaluation methods for R2S through the project timeline during early phases revealed that most methods in use address characteristics of system and detailed design. Methods used in early stages include confidence-based comparison matrices, and specific parameter assessments regarding the behaviour of prototypes. Reasons to reject solution alternatives during early phases were found from project milestones and the methods for R2S used in the project. Issues that were detected in early designs were repeated in later ones that used similar working principles. Design reuse in early design phases was related to doubts about the feasibility of ongoing alternatives, as there was a lack of clarity about specific problems with working principles. Issues with R2S attributes actually became less important in the transition from concept to system design.
Contribution to thesis	The paper contributes to the thesis in providing evidence of the lack of clarity regarding information about R2S attributes in early design phases, and in pointing out the consequences of reusing failed working principles – leading to the rejection of several alternatives in the process. This paper contributes to the thesis in relation to the need of support during early design phases.

4.1.4. Paper IV

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**Decision-making and feedback as foci for knowledge-based strategies supporting concept development**
Destination:	International Design Conference, DESIGN 2010, University of Zagreb and The Design Society (published)
Target Audience:	Researchers and advanced practitioners in Quality and Reliability Engineering for Product Design (conference presentation)
Motivation for paper:	Prior studies revealed the incompleteness of information from early design phases for the use of current R2S methods against their extensive requirements of data and expertise. It is relevant to describe the influence of design decisions and knowledge reuse as feedback originated by failures in solution alternatives from early design phases.
Research stage	Design Research Methodology: Descriptive Study: Influencing factors
Research approach	Longitudinal study: Document analyses, reverse engineering and interviews to collect information from an industrial project to develop the principle solution for an insulin injection pen.
Summary of findings	Early phases of the design process were distinguished by the number of alternatives developed to ensure the feasibility of functional requirements to mechanism designs. A set-based development pattern was recognized due to alternatives implementing the whole set of functions in the product, and due to designers continuously negotiating degrees of freedom across functions in several working principles. Variations in product architecture were found to be more frequent and significant with functions characterised by several interfaces and degrees of freedom between components. The repetition of failures was confirmed to be result of shortcomings in design reuse, found as result of inadequate understanding of the failure mechanism in complex working principles. A timing relationship was found between the development of new solution alternatives and the rejection of failed ones, which confirmed the role of reusing knowledge from design decisions to improve design solutions during early design phases.
Contribution to thesis	The paper contributes to the thesis by investigating the use of set-based development to address the development of alternatives in the whole functional scope during early design phases. It highlighted the influence of functional complexity that makes the reuse of failed working principles more likely during early design phases. This paper contributes to the thesis by defining the focus of developing support to assist the feasibility of solution alternatives during early design stages.

4.1.5. Paper V

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**The current use of engineering knowledge for evaluation and selection of solution alternatives during early design phases**
Destination:	Research in Engineering Design, Springer, ISSN 1435-6066 (submitted)
Target Audience:	Researchers and advanced practitioners in Engineering Design and in Design Practice (journal article)
Motivation for paper:	Design teams are required to evaluate concepts under conditions of significant uncertainty and to make short-term decisions because of tight project schedules. There is an interest in understanding the use of engineering knowledge in support of verifying the feasibility of functional requirements in alternatives during early design phases.
Research stage	Design Research Methodology: Descriptive Study: Influencing factors
Research approach	Longitudinal study: Document analyses, reverse engineering and interviews to collect information from an industrial project to develop the principle solution for an insulin injection pen.
Summary of findings	Clear descriptions of purpose (function) were found to be associated with expressions of uncertainty about behaviour, which expressed the lack of clarity about which specific components caused problems. The development of alternatives was found to be either divergent when more alternatives were developed in response to previous issues, or convergent when more alternatives were rejected against fewer ones proceeding. Repetition of failures was observed from one concept to another, due to the reuse of parts from previous concepts while neglecting original reasons for failure. Experienced designers had to adapt their experience to the new situation for predicting how component interfaces could be solved, but this was complicated by the fact that several possible pathways were available as solutions, which did not fit prior experience. Failure to learn from the first occurrence of failure during the project derived from the ambiguity of working parameters across several product architectures. This increased the effort to verify early alternatives due to the amount of information being handled, which accounted for the difficulty of using methods for R2S in early design stages.
Contribution to thesis	The paper contributes to the thesis regarding the current use of knowledge as a result of complexity in solution alternatives and in the protocols of current R2S methods. This complexity makes methods for R2S prone to error, because there are insufficient references about failure mechanisms on working principles and their parameters.

4.1.6. Paper VI

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**Requirements, development and verification of a design tool to codify engineering knowledge about attributes for failure and success of solution alternatives during early design phases**
Destination:	Journal of Engineering Design, Taylor & Francis, ISSN 1466-1837 (submitted)
Target Audience:	Researchers and advanced practitioners in Quality and Reliability Engineering for Product Design (journal article)
Motivation for paper:	The requirements of design information in current methods impose effort to verify and select alternatives, and prevent the reuse of this information within the ongoing design process. There is need of a tool to facilitate the process of verification, selection and improvement of solution alternatives during early design phases, due to the difficulty of having sufficient information available for current R2S methods.
Research stage	Design Research Methodology: Prescriptive Study: Support Descriptive Study II: Verification
Research approach	Observation: task simulation records, document analyses and questionnaires to collect information about the use of a card-based tool with proposed information structure about R2S attributes of solution alternatives.
Summary of findings	The tool was developed with a template associating the function/working principle pairs to behaviours triggering occurrences of failure and success. Participants felt the tool offered sufficient information, as they used individual records to justify their decisions and as bases for their suggestions of improvement. The tool required further development in relation to individual preferences, personal attachment, and factors of pressure in the selection task. Designers also felt pressed to adopt a single strategy to solve individual design problems. Nevertheless, designers engaged in decision behaviour, which was followed by a final judgment selecting the best alternative. Reasons to reject were identified and divided into those which were unsolvable and unacceptable, and those that could be solved through further work. Benefits linked to R2S in working principles were maintained, whereas those without such a link were not. Countermeasures successfully switched the use of failing working principles to improved ones, so that the tool has effectively prevented the recurrence of failures with reuse of working principles.
Contribution to thesis	The paper contributes to the thesis by asserting requirements and conditions for the development of knowledge-based support for early design phases. A card-like approach, which yields information about alternatives regarding R2S attributes used in review-selection-feedback routines, has avoided the reuse of failed working principles.

4.2. What information about product design do current methods for R2S need to generate information about R2S in a product?

This research question refers to current methods for R2S as systematic processes to aggregate information about attributes in design. They require knowledge about product components in their construction and working principle, the conditions of operation in use states and operational modes, and relationships of assembly and functionality that determine behaviour. Relations need to be determined between product components, between use situations and between states of operation, which cause behaviours which will either be suitable or not to design requirements.

For example, the slip and run-off failure identified in the insulin pen is characterized by slippage between a right-angle edge in one component and a straight, smooth surface, in another. Neither the friction between the edge and the surface is stable, nor is the assembly offer sufficiently rigid to keep the force level needed to hold the interface. Hence, there is uncertainty on the safe locking of the smooth surface component with the possibility of unlocking it. To assess whether separate operation modes are achieved, relations need to be determined within the edge-plane interface and between components in the assembly.

This requires knowledge of use situations, regarding activation of the edge component in a hurry, too slow or too strong, and also about states of operation of the plane component, if standing still during dose setting, moving during dose delivery or moving during medicine recharge. Assessing or evaluating characteristics like the slip-off failure in an insulin pen design requires the aggregation of knowledge about attributes that are essential to obtain its successful use.

This process is described in more detail on the following items.

4.2.1. Codification of information about R2S

Paper I focused upon the availability of specific types of information about design, and the feasibility of using current methods with the information that is typically available during early design phases. To this end, information about the behaviour of the washing machine was acquired from documentation and records, and then organized into categories. The types of information shown in Table 25 represent design characteristics that affect R2S attributes. These established a basis for assessing the availability of information to fulfil the queries of current R2S methods.

Table 25 – Keywords for information about R2S in product design

Keyword	Reference	Definition	Processing	Source
Function	Functional basis (Hirtz, et al. 2001)	Structured actions and system flows achieving a definite technical purpose	Retained original	Function model
Product	Engineering design (EDIT) (Ahmed, 2005)	Constructive elements, characteristics and relations from the designed product	Retained original	Organ model
Issue	Engineering design (EDIT) (Ahmed, 2005)	Relations, characteristics and requirements to be considered during product design	Retained original	Body model
Failure mode	Mechanical failure (Bloch & Geitner 1990)	Processes and phenomena causing degradation of performance or failure	Changed original	Body & organ
Event	Product dataset (Papers I, II)	An occurrence where system properties and/or the functional state is changed	Created from data	Body model

Information from concept design identifies system components, their modes and states of operation; direct dependencies (foreseeable) between event and effect are also described – backlash between gearing pairs in a gearbox will induce increased wear and noise, or degraded accuracy in timing or positioning, for instance. However, information for conditional dependencies such as situation-dependent events (FTA), provisions (FMEA) and safeguards (HAZOP) is poorly determined – it is not possible to determine the causes to loss of balance in the drum (washing machine) without simulation or working prototypes.

As seen in Paper II, sketches – such as the freehand exploded perspective of the washing machine – identified and clarified design elements such as components (product information) and their purpose in systems (function information). Diagrams and reports were valuable as they clarified and structured information about states and behaviour of working principles – on the washing machine example, function flows in the drum helped identify cycle times with different behaviour and parametric descriptions such as drum speeds characterized the effects from steps in the washing cycle.

4.2.2. Practical use of R2S methods in design

The findings in paper II describe how the demand for different sources of information, and their processing with the use of current methods in design, was fulfilled by the concurrent use of several design models. A single sketch of the drum – in the washing machine – will only describe how components are arranged in the drum; properties such as loads in moving parts and loading regimes during operation may be recognized upon either prior knowledge about such characteristics or the availability of additional descriptions about these aspects.

Design models could be selected on the kind of information they provided to assessing R2S attributes: Explicit information about R2S in early design models consisted of: the contour geometry of the body diagram and the freehand exploded sketch characterized the *product;* icons in the body diagram of the washing machine represented direct relationships of force and movement involved in *issues;* and pairs of geometry and component icons that conveyed the implicit notion of function. However, more complex types of information such as *failure mode* and *event* were missing.

Two scenarios to such information exist: on the washing machine, information on past designs was available through manuals of existing products or maintenance web sites; in the second scenario, a discovery process is required as no other design has similar function and working principle. Assessments of R2S attributes in adaptive designs could be carried out by similarity: a suspension design that is similar to prior art may also have similar issues. If components such as those from the suspension of the washing machine are changed to original designs due to new requirements like needs of space or to reduce cost, no similar issues can be found.

4.3. How does information about R2S from concept design influence practice to improve R2S on solution alternatives?

This research question refers to information about R2S as guidance for decisions about solution alternatives and input for improvement priorities; in the industrial case, this was found to be established through the use of purpose-specific routines (e. g. parametric measurements) or current R2S methods. Here, designers were found to establish decision criteria to interpret the performance of alternative designs; these criteria reflected the degree to which alternatives were evaluated as meeting the requirements in each design phase.

In the insulin pen project, the decision to reject the A4 design and proceed with A5 and A32 was found in Papers III and V to be supported by evaluations of performance parameters in the ‘C’ and ‘D’ milestones – see Figure 1. The A4 alternative was seen by designers as working well: from CAD models and prototypes, positioning throughout the gearing/threading chain was found as acceptable. However, evaluation reports and designers´ statements about A4 pointed out characteristics that were detrimental to positioning accuracy over time, which caused them to wear out and creep too early in performing the same functionality as the others.

Such characteristics – accessible through sufficient level of detail in models – motivated the rejection of that particular alternative and guided designers to work on other alternatives with better performance on functional requirements (A5 and A32).

This reflects the choice of design efforts that are both affordable and generate improved performance to design requirements as practice to improve R2S. However, inconsistencies were found between the designers understood issues as motivating rejection of designs (information from R2S methods) and how they reused that knowledge to solve that problem. These inconsistencies occurred mainly in functions with more physical interfaces, which had the result of similar failures being repeated throughout early phases as result from reusing flawed designs – see Figure 2.

It is thereby shown that the stroke-out (A6 reusing O2 design) and the slip and run-off (AS2 reusing S3 design) failures were repeated for the same function; working principles for this function were found to have a minimum of 10 physical interfaces across all alternatives. This complexity made it more difficult to distinguish where a past design has failed and therefore the repetition of failures upon design reuse took place. The identification of knowledge that can be reused about alternative designs was carried out in the industrial case through tracking down incidents such as described above.

This process is described in more detail on the following items.

4.3.1. Practical use of methods

Papers III, IV and V were concerned with the influence of R2S methods on early design. Evaluations on R2S attributes of alternatives were found to be carried out less frequently during the earliest phase, in comparison to a higher frequency during and after system design. This was due to significant resources being allocated to the actual construction and development in early phases, as several alternatives were developed in parallel; evaluations of product attributes in early alternatives (all Sx and Nx as in Figure 9) were carried out with less formal protocols such as comparison matrices involving scores on functional requirements (dosing force) and generic performance characteristics of the product (reliability).

This kind of evaluation essentially relied upon the experience of the engineers involved, which influenced the development direction in alternative designs. Paper IV showed the direct relationship between decisions made about solution alternatives (e. g. to reject) and the development of further alternatives (shown in Figure 9), in particular during the earliest phases. ‘C’ and ‘D’ evaluations motivated the rejection of five alternatives (A1, O2 and all ASx), which were seen to trigger the need to develop new designs; these new alternatives (A5, A6 and A32) were designed with new components for the internal mechanism, based upon past designs that were rejected but were seen as promising.

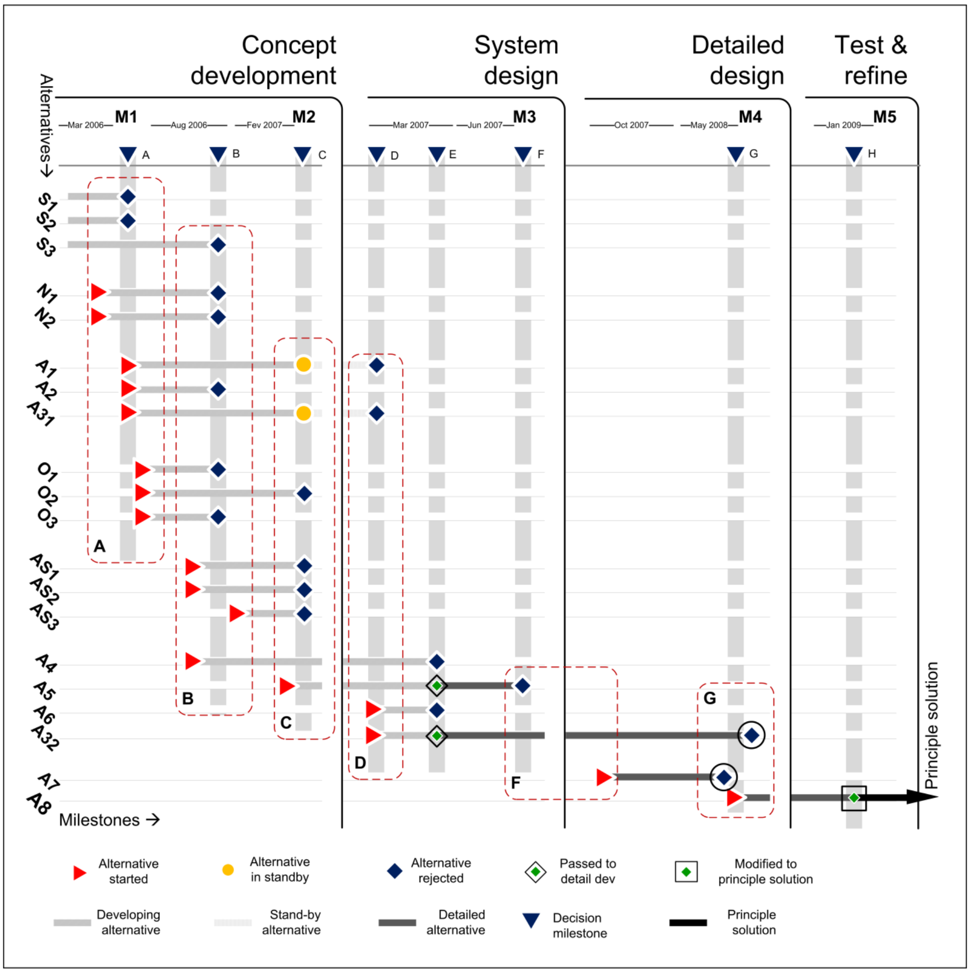

Figure 9 – Decision-feedback chains across the development of alternatives during early design phases

During the industrial study, several alternatives were thus developed in parallel during the earliest phase as displayed in Figure 9. Due to the resources needed to generate design models and extract proof of performance, each alternative had a limited time for development. In addition to that, little use was made of more structured methods to evaluate solution alternatives in early phases. Hence the issue with the detection of the origins and mechanisms of failure in early design as with the repetition of failures from S3 and O2; current R2S methods such as FMEA and HAZOP were only used when the final design was ready.

4.3.2. Consequences for design strategy

Due to the complexity of several architectures and working principles, motivations for rejection were often dismissed or forgotten through a chain of decisions. The A6 alternative was designed with an edge-plane interface for the purpose of locking – reusing the same design from O2 previously rejected because of a slip and run-off failure, see Figure 10. This displays a lack in architecture-generic methods to evaluate designs: the new architecture in A6 led to the belief that the failure mechanism was mitigated and could be dismissed.

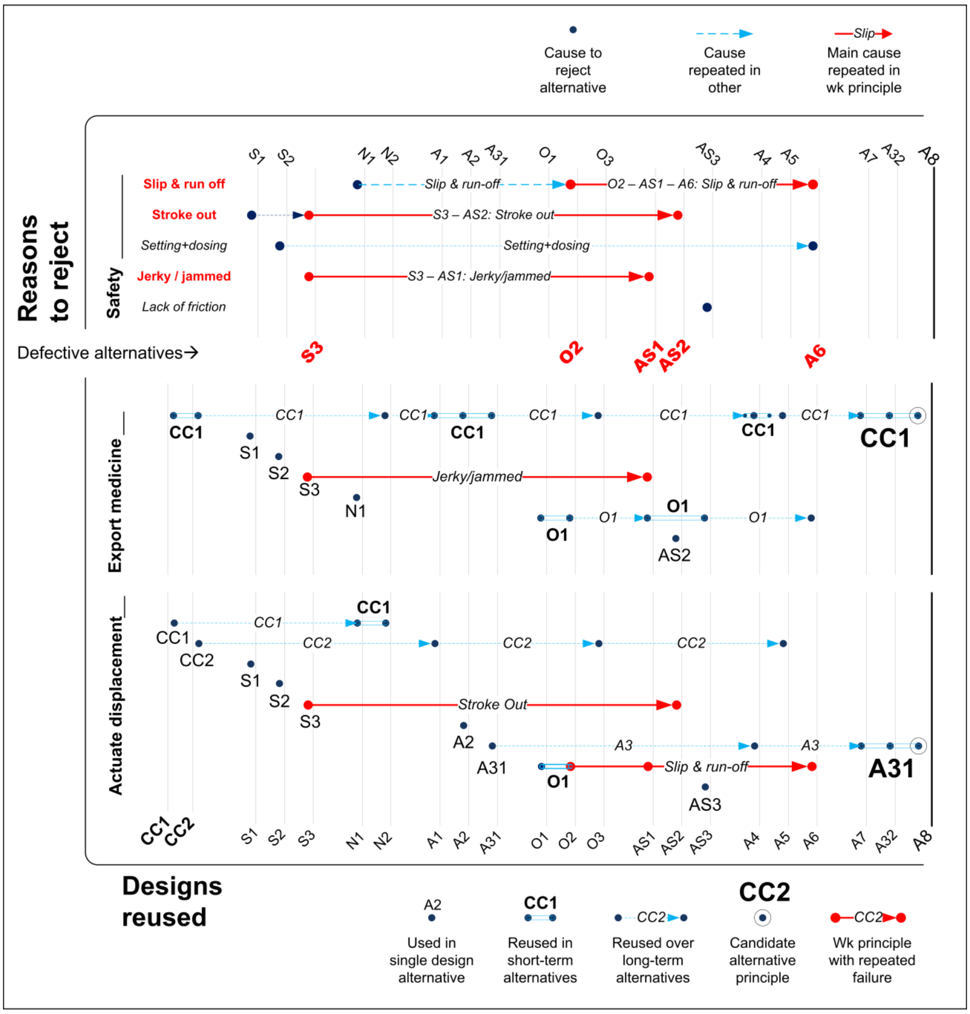

Figure 10 – Designs reused in relation to reasons for their rejection during early design phases

As ascertained by Papers III and IV, designs that previously failed were reused in new alternatives. This was found more often in more complex components linked with several others performing different functions in the system architecture. The components in use for actuating the displacement of the medicine were those most prone to failure due to the sharing of functions among them. The number of interfaces of a component to relay the spring force to the piston has caused designers to use more complex geometries to include all necessary kinematic pairs transmitting or constraining movement.

As seen in paper V, the complexity across several architectures thus caused ambiguity in the evaluation of issues. Designers had to iterate more frequently through the same design issues – developing a number of different alternatives – instead of advancing with the project. Hence, a cumulative influence from early alternatives to the rejection of later ones could be verified from the relationship between methods, decisions and new designs. This escalated the impact of complexity across alternatives, delaying to the convergence towards a solution principle.

4.4. How to model information about R2S in alternatives for methods that elicit practice to improve R2S during concept design?

Methods describing problems in solution alternatives often used language which was distinct from that in use by designers in conversations and less structured methods. The thought process driven by queries in methods for R2S, and their arrangement, should be more accessible to designers. Sufficiently complete descriptions in similar level of detail are needed about characteristics of the designs that influence R2S attributes, in opposition to the current process where design descriptions evolve with development and change significantly.

In assistance to these goals, a prescriptive study was carried out to generate a design tool supporting designers in the selection of concepts based on prior knowledge of known issues. To reduce the dependence of design descriptions from available detail, a visual approach was designed to aggregate all characteristics within a single visual field. These characteristics were defined from generic categories of information about R2S attributes contained in a design taxonomy developed from the pilot case, benefitting from the results found in the industrial case (see Papers II, V and VI).

The display of the tool (Paper VI) implemented this formulation by rendering alternatives, pointing out individual issues and describing how they evolved in the same view. The characterization of issues was intended to guide engineering judgment in decisions, whereas the rendering of alternatives was intended to inspire ways to improve the issues that would remain from the decision process. The description of how issues evolved and how solutions are intended to solve them comprises the following categories in the taxonomy:
function > product > issue > failure mode > event > consequence.

The development of the design tool is described regarding the design of the visual layout and the definition of the use process, as in the following items.

4.4.1. Codification of R2S in methods

Traditional methods for R2S in the project used specific terminology about product attributes, requiring effort to interpret design characteristics within their mind-set as they consider different characteristics individually. For example, FTA analyses performed with the principle solution required designers to translate their predictions of incidents in natural language to a specific form amenable to the analysis. This is quite different from the natural language employed by designers, as shown in Table 26, where they associate the different characteristics involved in a single design issue.

Table 26 – Information about R2S from methods in early design and from designers' descriptions

Query	Example in method		Taxonomy	Statements	Relation
SETx: Possibility of ½ IU/U200	**Table:** "Yes"		**Issue – Functional requirement**	"If there should be half increment, sheet metal gives less on that focus"	**Function → Product**
EVA: Dose button **/ dose set-up /** *mode change*	**(a)**"Range: 0 to *max* in 1 IU steps, possible dial up and down"	**(b)** "Flat torsion spring (...) Assembly status in CAD (...)"	**(a) Issue – Functional requirement** **(b) Product – Geometry**	"Half these teeth has to be very fine (...) talking about x.xx mm per unit"	**Issue → Product**
SETx: Accuracy reading	**Table:** "2"		**Issue – Product characteristic**	"The position of the dosage tube is what we are actually measuring"	**Product → Function**
EVA: Accuracy / *sensor*	**Report:** "The position of the piston depends on the rotational position of the ratchet and the precise locking between the base part and the ratchet."		**Issue – Product characteristic**	"what you actually make the sensor of, it has to be without any gap"	**Product → Issue**

Findings such as from Table 26 formed the basis for developing a display of categories of design characteristics influencing on R2S attributes (Paper VI). The relation "if there should be half increment, sheet metal gives less..." suggests that slender components have less stiffness, not being favourable to narrow position increments; all alternatives with such characteristics would be discarded if more increments within a same displacement were needed. A structure was required to codify information about R2S, which is simple yet complete regarding influences to R2S attributes, for reading within a single view like taking part in a conversation.

The types of information about the product to assess R2S attributes were verified first, in comparison to the taxonomy from Paper I and II; as a result, another type of information, 'consequence', was identified due to the designers' need to assess the ultimate consequences of failure in the use environment. Then visual layouts were developed to allow all such types of information to be visualized in the same field; strong focus on card-like records resulted from to the need to elicit designers' own knowledge about the mechanisms involved in design problems, as it is shown in Paper VI.

In order to address this, a main piece of the card-like formulation is the rendering of the alternative with icons to emphasize the component or the characteristic being affected by the individual design issue – then the issue is described in natural language statements following the categories of the taxonomy.

4.4.2. Practical use of methods

The findings of the industrial case revealed that current methods for R2S involve comprehensive cause-consequence descriptions of how the product works or could possibly fail; therefore, they require a 'pool' of input information to be assembled prior to their use. However, early design phases in the project were characterized by a discovery process about product attributes by the assembly of parametric relationships from working principles in different models. For example, alternatives with dosage tube components that were not similar to the current had to be reassessed prior to judging how these designs performed.

This reassessment involved discovery iterations where information was aggregated about the new designs and their functional attributes. However, the link between decisions made and references to new designs was found to be incomplete in early phases, which creates flaws in this discovery process. Table 27 shows, among other things, that views about the reuse of knowledge about tolerance issues for new alternatives "sure that this will be able to follow" diverge from the views about alternatives rejected because of tolerance issues "you bend and you don't know how it returns".

As in the studies in Papers V and VI, this demonstrates that the information flow between decisions made and the reuse of knowledge for improving alternatives was not always smooth, due to inconsistencies between different characterizations of the same problems. The documented inconsistency between different views on the same aspect, changing from reasons to reject towards directions for improvement, showed the need for greater correspondence between design decisions and knowledge reuse to further design tasks.

Table 27 – Inconsistencies in information about R2S between decisions and knowledge reuse

Decision	**Knowledge reuse**		
Reason to reject	**Types**	**Example**	**Documented**
Interview: "Very good tolerances when you stack them; you bend and you don't know how much it's going to return"	**Tolerances**	**Interview:** "You have the movement of electronic (…) you should be sure this [components] will be able to follow each other.	Gap in linear components Dripping
Interview: "Very small parts to be machined, and high friction because there's a lot of interfaces between components"	**Friction**	**Interview:** "The piston rod in this system was… not easy to retract There's a lot of interfaces, and the complexity, I think so."	Solve friction conditions
Interview: "We needed to be sure whether it could deliver individual increments but there was a chance it would slip a little"	**Sensor interface**	**Interview:** "If you want to mix mechanical and electronic concepts, you must be aware that you haven't got so much gap."	Prepare for electronics Improve clicks

For this reason, another requirement for the design tool in support of R2S attributes during early stages was to facilitate direct correspondence between problems manifested in previous alternatives and knowledge reuse for the improvement of the remaining alternatives. A significant issue found in traditional methods for R2S is their focus on storing information for later retrieval, rather than giving immediate feedback on design issues so that designers could work on solving them. This was addressed by setting the use of the tool as a design review-and-selection process.

4.5. How does the proposed model of information about R2S support practice to improve R2S during concept design?

The tool developed in this study was intended to elicit the designers' own 'knowledge' of the product in relation to key functional requirements, non-desirable behaviours and better-performing working principles. This was verified through 2 evaluation interviews and a use simulation task. The first interview was carried out with the risk specialist alone, and the second interview involved six design engineers from the partner company. The use simulation task involved three participants from the second interview, plus other design engineer.

From the participants in the second interview, three designers had 3+ years expertise, two designers had 7+ years expertise and one had 15+years expertise. In the use simulation task, there was one experienced designer with 10+ years of practice, two other designers with 3+ years of career and the risk specialist with 15+ years of experience. The researcher was observing the activity. Interviews were recorded in written notes, whereas the use simulation task was observed and video-recorded. In preparation to the use simulation task, designs from the original project and respective issues were characterized with the tool.

The first session was intended for designers to choose the best alternative among 62 records of issues available about 8 alternative designs. Then, the second session was intended for designers to treat the 5 remaining issues about the alternative they chose in the previous session. The performance of designers using the tool was verified by comparing the outputs from the use simulation with the work performed by designers in the original project in the following criteria: failures that were avoided; and failures that were corrected (paper VI).

This research question refers to the verification of the proposed model of information about R2S as driver of practice to improve product design. The verification of the tool is described in the following items.

4.5.1. Codification of R2S in methods

The verification study explored the result of the approach set in the tool to codify and use information about R2S during early design stages. Regarding the codification of R2S attributes, the study considered whether practitioners were able to learn how to read the records and use their content to select the alternatives which, in their view, were best suited to fulfilling the design requirements. This was a test on whether the tool was using language that was amenable to practitioners, with a natural thought process to their form of practice.

The reaction from participants was obtained by assessing their overall attitude towards using the tool. During evaluation sessions, participants were willing to say their views about the tool; from the second interview, designers judged that the layout and the navigation made sense to search and retrieve information about solution alternatives. Participants in both interviews agreed that the tool was providing better information than in their practice: the grouping of several information fields around individual issues was useful reproduction of their thought.

Designers found the codification approach to be susceptible to individual preferences, attachment to own designs and other priorities in product development. For example, If an individual designer sees certain alternative as ‘looking better’, or the manager *wants* a given solution regardless of the views interpreted by other users, the information provided by the tool becomes subject to this kind of bias. Nevertheless, designers found the graphic layout to be helpful in visualizing design problems and associating them with the performance.

4.5.2. Practical use of methods

To assess how the tool worked in supporting decisions and eliciting improvements, a use simulation task was set up where participants were asked to declare the rationale of their work in the two parts of the exercise. In the first session, designers actually used the tool in the following phases: they skimmed through records, noticing reasons to reject alternatives; then there were records they got back to, seeking clarification from the risk specialist; then they recalled alternatives in a later phase to ascertain limitations on their own; finally, they chose the best alternative they found on through the exercise.

Figure 11 shows the way designers went through in the first session. The activities that designers engaged regard individual alternatives, and consultations to sources such as original renderings of alternatives (Or), instructions to use the taxonomy (Df) and consultations to the risk specialist (Fa). Few alternatives were rejected in within browsing phases, which indicates designers took more time to see the content of records and discuss the respective issues. Two alternatives were later recalled, which indicates designers clarified their judgment.

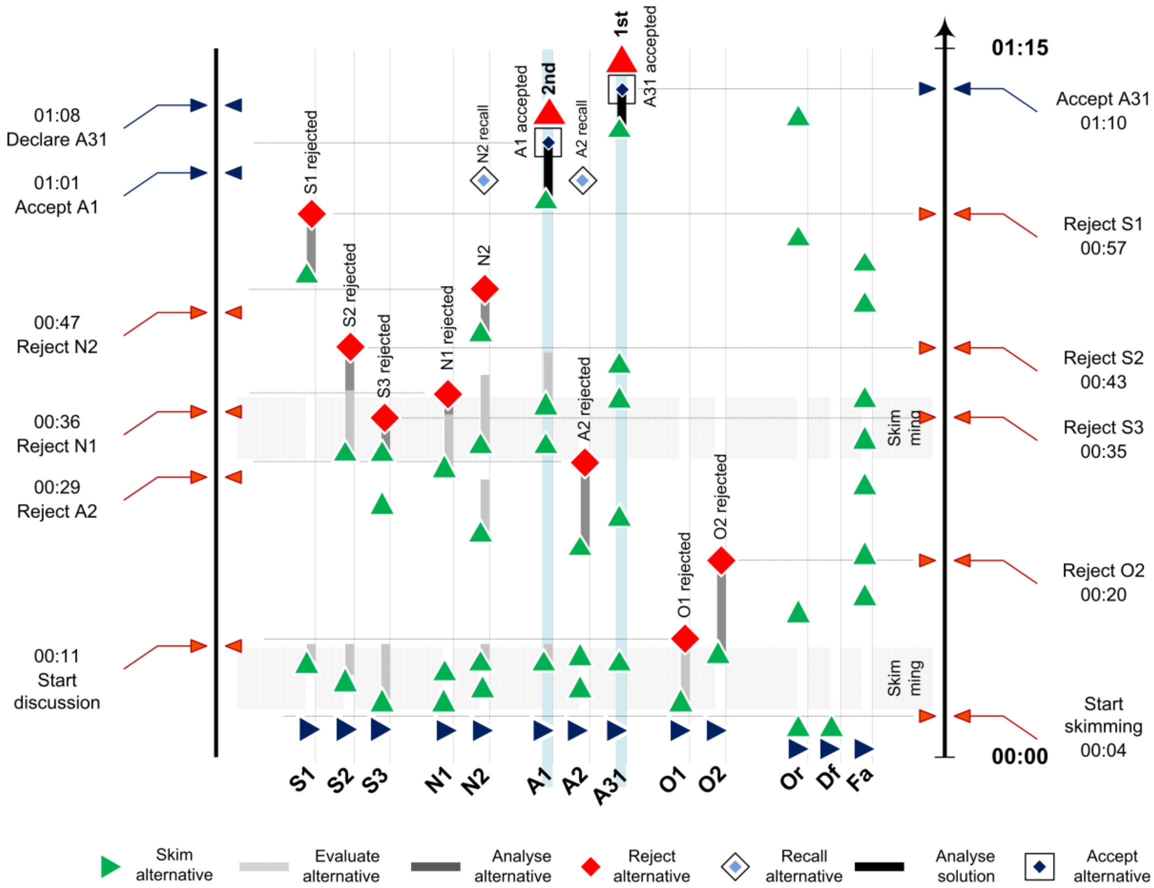

Figure 11 – Decision timeline to R2S attributes among alternatives with the use of records

In the first session, designers were able to reject alternatives manifesting failures against R2S attributes by using the tool: they selected the alternative whose benefits added more value to the project – A31 displayed significant benefits to function such as accuracy. In the second session, designers managed to solve outstanding issues with the chosen alternative, thus emulating the winning strategy implemented in the original project. Therefore, designers were able select suitable alternatives, although lacking familiarity with the tool.

This assessment is based on the following characteristics that were raised by designers after the first session: number of individual records of failure and benefit by alternative; criticality of failure/advantage from benefit to required functionality in designs; and, accessibility of solutions to issues from their own knowledge. The validation of the tool concerned whether designers rejected alternatives with significant problems, and whether they accepted those presenting more benefits, whose problems were easier to solve.

Safety failures led to outright rejection of alternatives. For example, designers distinguished a flawed design like O1 and rejected it first-hand, as this alternative had 3 records of failure and 1 record of benefit. The alternatives with unsolvable reliability issues were rejected at the beginning of the exercise after brief evaluation. The O2 and S2 designs were rejected on the grounds of designers having perceived ambiguity - O2 on the edge-plane locking interface and S2 was rejected because of friction and excessive interfaces whose degrees of freedom could not be enforced. Better designs such as N2 and A1 were not compared internally but also with other designs, which took more time to evaluate. The last round involved the recalling of N2 and A2 along with a review about A1, in positioning accuracy and kinematic pairs.

Through showing the remaining issues in the second session, the tool called designers to express their knowledge about how to solve them, with focus on improving R2S attributes. Two different types of solution were proposed: the first was to increase the stiffness of the threaded component for setting the dose, which was proposed to be tuned up by handling the material selection along with the cylindrical thickness; and, the second was to work up the contact area between this component and the base structure with bearing support in order to reduce local friction throughout the use of the device.

Two modes of improvement were then identified: the first was to correct dimensional and material properties of a component without significant changes to its working principle; and, the second was to integrate/differentiate components, to switch from ineffective working principles to others designers knew as having positive effect against particular failure mechanisms. The solutions suggested by designers counteracted the problem in ways comparable to the resulting solution principle from the original project.

4.6. Where does this all take?

The results discussed in this chapter point out to the need to codify and express knowledge about how working principles are effective – or not – in performing to certain functions requirements. This is important, for instance, to select parallel or helical movement assemblies to position a mechanism: which of them will make less wear, or which of them will be more accurate? Working principles failing to these requirements would not possess the R2S attributes needed to ensure successful operation and use of a design.

The findings described in this chapter regard the following aspects: how design characteristics interconnect to each other (research question 1), on how these influence engineering judgment upon the choice of alternatives (research question 2), and on how this process can be improved (research questions 3 and 4). The results obtained contribute to a better understanding about strategies to achieve requirements by enabling the use – and reuse - of expert knowledge about this kind of decision.

Chapter 5 - Discussion of findings

This research is carried out in the intersection area of two fields: knowledge management in engineering and design, and systematic methods for improving robustness, reliability, and safety. The research is motivated by the need to enable designers to carry out R2S assessment in early design phases, under circumstances of uncertainty about R2S attributes, and ambiguity on the variety of solution principles. This chapter discusses the contribution of this project in three areas: first, the contributions to research; second, the implications for industry; and third, the limitations of this project, which all together serve as a guide to future efforts. These elements are addressed in the following sections.

5.1. Contribution to research

This research has been carried out in the field of engineering knowledge management applied to R2S attributes in engineering design. Focus is applied on codifying information from early design phases to communicate R2S attributes of solution alternatives, considering the flexibility needed under intrinsic uncertainty and ambiguity during concept development. While current methods for R2S rely on extensive data and individual expertise, knowledge-based approaches are envisioned to accommodate practical situations by eliciting input from the pool of information and experience in the organization.

The contribution to research from this thesis comprises the following:

- Assessment of the performance of current R2S methods with early design information;
- Investigation of current use of early design information to evaluate R2S attributes; and
- Codification and use of design information to converge onto required R2S attributes.

The performance of current R2S methods relates to the cost of eliciting R2S attributes by current methods for scarce information during early design phases. The use of design information to evaluate R2S attributes refers to the flow of R2S attributes through design tasks and its problems, such as the ambiguity in source information during early design phases. And, the approach to codifying and using design information directly consists of the development of a record-based design tool that structures information to support engineering judgment and elicit knowledge about the R2S attributes of alternatives. This is intended to help the progress of designs converging into a successful principle solution.

5.1.1. Performance of R2S methods: eliciting knowledge on the product

Current R2S methods were found to be either too cumbersome for use during early design, or found to lack tolerance to ambiguity among configurations. This included the identification of shortcomings of current methods for R2S in handling information being generated during early design phases. To this end, this research included a pilot case about current methods for R2S attributes, which was performed with a washing machine. The main issue for the application of current R2S methods in early design phases is *a lack of accessible information for current R2S methods, as meaningful knowledge either does not exist or is unaffordable from the available information during early phases*.

Current methods for reliability and safety approach the system as a logical connection of components possibly in the form of a causal model, which is yet to be developed and consolidated during conceptual design. At the same time, they need characteristics of the design that are yet to be well-defined as input, such as the conditions of operation during use, and dependencies of assembly and functionality. The incompleteness or absence of clear descriptions or guidelines for these characteristics generates the difficulty in the use of current R2S methods during early design phases. Predictions of design issues cannot be completed with current methods, as the product is yet to be defined in its characteristics of use, and in the dependencies needed for the methods.

More recent contributions in this area, as shown in Table 28, intend to address this matter for conceptual design. Approaches to early assessments of reliability (Smith, 2002; Derelöv, 2008) rely on the organization of structured descriptions of predicted or observed product behaviour. Smith's (2002) approach focuses on the assessment of component characteristics, whereas that of Derelöv (2008) works by recording observed behaviour in a database. Both techniques depart from the characterization of working principles through their components and their manifested behaviour. Such structured organizations of information about product designs reproduce the escalation of individual problems into impaired product performance.

Another approach consists in counting dependencies between historical cases and generic functional models for a category of products. This technique maps failure modes through the interpretation of the functions performed by the failed components, where working principles are implicitly considered (Tumer & Stone, 2003). This form of reasoning is expanded to calculating the likelihood and extent of consequence as a risk method for early design phases. This approach gives priorities to the choice of working principles for alternatives and their evaluation (Lough, Stone, & Tumer, 2009).

Table 28 – Comparison to other studies regarding the elicitation of knowledge

Industry/ref	Design tool [this study]	Reliability model [Smith, 2002, Smith & Clarkson, 2005]	Failure database [Derelöv, 2008]	Risk-to-function [Lough, et al., 2009]
Type of product	Medical device	Crane machinery	Ball bearings	Spacecraft
Size, scope, no. parts	Small, whole product $n \times 10^1$	Large, subsystem, $n \times 10^1$	Small, subsystem, $n \times 1$	Small, subsystem, $n \times 10^1$
Complexity	Medium	Medium	Low	High
Damages from design flaw at use	EUR $\times 10^7$	EUR $\times 10^5$	EUR $\times 10^6$	EUR $\times 10^6$
Focus area	Eng. design, knowledge mgmt.	Eng. design, DFx	Eng. design, DFx	Eng. design, risk management
Methodology	Prescriptive study and descriptive II	Prescriptive study and descriptive II	Prescriptive study	Prescriptive study
Design phase	Concept design: decision and reuse as feedback on designs	Concept design, iteration of design alternatives	Concept design, evaluation of working principles	Concept design, selection of principles to alternatives
Source data	History of failure and benefit attributes of alternatives in early design phases of an R&D project	Test case from industry using assembly drawings, design data and project documentation	Test case in laboratory using manufactured product and reverse engineering	Generic functional definitions, historical counts of failure in similar functions
Type of method	Keyword-based fields in graphic card layout	Node-link-branch from flow diagram	Framework from information model	Matrix-parametric strength relationships
Source of information	Assembly cutaways, augmented with icons	Exploded assembly drawings	Manufactured products	Specification, drawings, prototype
Verification setting	Simulation task with industry practitioners	Simulation example with industry project	Simulation example with academic work	Simulation example with government project
Validation of performance	Comparison of practitioners in industry using the method and results from original project	Review of output from researcher by practitioner in industry	Supervisor reviewing output from primary author	Comparison of function-based assessment to ongoing risk assessment in space project

The risk-to-function method helps to select known working principles based upon the counting of actual failure records as it aggregates historical information on existing products around a generic function model (Lough, Stone, & Tumer, 2009). The reliability model is based upon common-sense design guidelines and principles that are applicable to embodiment design, better suiting the review and iteration of individual designs (Smith & Clarkson, 2005). Then, the behaviour model (Derelöv, 2008) helps predicting failure modes in working principles from a computer database of failures and their cause-consequence chains in known components.

As from the methods shown, the discovery of issues to R2S attributes is driven by the need to know about the feasibility of conceptual designs for a new product. Methods for R2S support design work during early phases, but the following shortcomings hamper their actual use:

- Product behaviour databases require specific infra-structure in the form of software applications which carry the same complexity as the original methods for R2S;
- New techniques for assessing behaviour of early product designs require specific knowledge outside the expertise of practitioners in industry; and
- Most design issues could be clarified anyway with support from simulation models or from prior design expertise applied to the new situation.

Methods for the choice of working principles such as risk-to-function lack transparency in their mechanism of determining suitable working principles, because mathematical functions are applied to qualitative scores whose origin is not clear. If one applies transfer functions on a physical quantity such as when transforming time to frequency, the math will return another physical quantity. However, transfer functions and mathematic techniques on qualitative scores will return a score of preference or perception that is known for insiders but is difficult for other engineers or decision-makers to understand.

Predictive models such as those based on the failure database could be too cumbersome to maintain, because of the complexity of the information model and essential effort to develop and keep (operate?) suitable software. Current search tools in document management software can provide information about a journal bearing that belongs to a ship engine design, but do not change the fact that current R2S methods require comprehensive input. Complete cause-consequence models of failure mechanisms are highly sought-after information, but the proposed tool creates additional work to collect the data from the engineering office.

Qualitative approaches to reliability modelling would then require an additional system of reasoning that is not quite accessible to practitioners who evaluate early product designs. The flow-chart interface of the tool is by large domain-independent, which allows its application is several domains beyond mechanical components. However, using the tool requires significant training as the complexity of its logic demands on the reasoning ability of designers, and the gain of expertise and confidence takes significant time to develop.

The method developed in this thesis has directly rendered product characteristics along with the R2S attributes they were associated to in the form of individual records of failures and benefits. By using such information in review-selection-feedback tasks designers were able to assess the feasibility of design alternatives, select most suitable and converge to the characteristics of a preferred solution. Paper VI has shown the successful application of the tool in a proof-of-concept evaluation, regarding the avoidance of reusing failed working principles and the solution of outstanding issues converging to a preferred solution.

5.1.2. Current use of design information: focus on effective use of knowledge

Information requirements in current methods for R2S were found as preventing their completion in early stages. These include consolidate relationships regarding functional requirements and design variables: their use requires experimentation with simulation and/or prototyping tools. Because of the interest in understanding how this is handled in actual industry practice, an industrial case was carried out on the development of an insulin pen. The main issue in the use of design information to R2S attributes is the *scarce information about how alternatives function (not about how they are intended to function) during early phases*.

Current methods for reliability and safety are only used in industry once there is a final principle solution. Experiments are carried out on global parameters, to compare overall performance among alternatives. There are two problems here: methods for reliability and safety are simply unfeasible, and methods for analytical robustness are difficult to apply to several architectures at once. Hence, tolerance stacking methods (Chase & Parkinson, 1991) were widely used once there was enough information about embodiment design where tolerance data from similar components in prior projects could be used.

This kind of analysis required a longitudinal study to be performed in a single case due to the complexity of the design process as practised in industry. Other contributions from case studies with industrial projects, as shown in Table 29, convey similar concern for the use of knowledge during early design phases. Inquiries about FEED (Front-End Engineering Design) projects of chemical test rigs and offshore equipment (Hales, 1993; Vianello, 2011) differ in regard to the scope of design tasks. Hales (1993) considers the feed-forward communication of design information to more detailed stages, whereas Vianello (2011) focuses on the feedback communication from service engineers to development engineers.

Another area where longitudinal studies make significant contribution to understanding the use of knowledge regards the development of a bumper forming technology for a concept truck (Legardeur, Boujut, & Tiger, 2010). While the types of data sources are similar to the other projects here considered – including this study – the interest of Legardeur and colleagues (2010) focuses the motivations of stakeholders in the project for developing a heavy truck bumper, whose development was then aborted. The interplay of interests is elucidated with a similar approach to that of the prior studies.

Despite the apparent similarity in the methodologies and in the types of data, the studies from Table 29 regard different scopes during the design process and a different view on problems or failure. In the one hand, the bumper truck concept project sees failure as a result of the mechanisms' interacting interests, with little influence from design feasibility, as the technology was known (Legardeur, Boujut, & Tiger, 2010). In the other hand, the offshore FEED study regards problems that arise from a lack of knowledge of relevant information; implications from design to R2S attributes in service could be missed due to miscommunication across phases of the product lifecycle (Vianello, 2011).

Table 29 – Comparison to other studies on the use of design information (adapted from Paper III)

Industry/ref	**Technology R&D** [this study]	**Product concept** [Legardeur et al., 2010]	**FEED Design** [Vianello, 2011]	**Test rig dev.** [Hales, 1993]
Type of product	Medical device	Automotive	Offshore hydraulics	Chemical process rig
Size, scope, no. parts	Small, whole product $n \times 10^1$	Medium, subsystem, $n \times 10^2$	Large, subsystem, $n \times 10^3$	Large, whole product, $n \times 10^3$
Complexity	Medium	High	High	High
Damages from design flaw at use	EUR $\times 10^7$	EUR $\times 10^5$	EUR $\times 10^8$	EUR $\times 10^6$
Focus area	Eng. design, knowledge mgmt.	Eng. Design, Actor networks	Eng. design, knowledge mgmt	Eng. design, design management
Methodology	Descriptive studies, prescriptive study	Descriptive study	Descriptive study	Descriptive study
Design phase	Concept design: evaluation of alternatives	Detailed design, dimensioning and process design	Detailed design, dimensioning and testing	Embodiment design, dimensioning and layout design
Source data	Bench CADs and prototypes in early stages; detailed models from system design	CAD body models, assembly drawings and process specifications in design documents	Development project documentation with CAD models and math-based simulations	Development project documentation with design schematics and CAD assembly drawings
Industrial setting	R&D project developing a new insulin injection pen	Development of a front bumper for a new concept truck	Development of hydraulic subsystems for offshore platforms	Development of a test rig for evaluating a new chemical process
Focus of study	Occurrences of failure and benefit across solution alternatives and working principles	Communication networks for material specifications and forming processes	Reports from service engineering of offshore equipment used by design engineers	Documentation of embodiment and layout design from test rig development
Data collection methods	Document analyses, reverse engineering and interviews	Document analyses, interviews and observations	Document analyses and interviews	Document analyses, interviews and observations
Context of findings	Comparison between working principles in and occurrences of failure, timing of evaluation methods throughout the project	Observation of motivations and conflicting goals across several stakeholders, involvement of actors through the project	Relevant knowledge exchanges between actors through the product lifecycle, and needs of knowledge by these actors	Engineering resources allocated to design tasks and basic information communications to product development

The study about the development of the chemical test rig draws insight from identifying of resource requirements for different phases of the engineering design process (Hales, 1993). From this and the other studies, the perception of how knowledge is used in the design process essentially depends on the factors influencing the awareness to new knowledge. As seen in the studies under discussion, such factors of influence relate to the interests of specific people and organizational politics, to the awareness in the organization about relevant knowledge towards improvement, or to a keen understanding about the information needed throughout engineering tasks. These factors contribute to engineers making choices of scope across the aspects that influence the development of technical attributes during early design phases, in the following senses:

- Along with market characteristics, the interactions of interests and power-plays among stakeholders drive the prioritization of other issues off the scope of R2S attributes;
- Lack of knowledge about service performance and situations during operation leads to lost opportunities of improving R2S attributes in front-end engineering tasks; and
- Project documentation will always provide a basis for feed-forward exchanges, but it is necessary to select and elaborate the information about R2S attributes and quality.

The approach to actor network theory by Legardeur and colleagues (2010) gives a broader vision of the factors influencing the success of a project, where characteristics of use in regard to R2S attributes form a single unit which is too specific. Knowledge exchanges as investigated by Vianello (2011) promote communication about design attributes, but there is need for more specific means to help interpret knowledge. Feed-forward prescriptive models establish basic frameworks of action, but lack guidelines for the prioritization of technical attributes.

In response to these issues, this study yielded relationships across alternatives and design tasks clarifying the need to support R2S attributes.

- Evaluations of alternatives determine the clarity of reasons for their rejection/selection; and,
- decision-feedback chains influence design efforts to ensure the suitability of new alternatives to solve previous problems.

These factors of influence have significant effect on the convergence of alternatives in early design phases towards the principle solution. The ambiguity and uncertainty of information used as input to R2S stem from the lack of support for evaluating several unique designs from formulations in current R2S methods. This is due to the deficiencies of current methods that focus on relations between component designs and their behaviour, with few explicit references to desired functionality and how R2S attributes are affected.

5.1.3. Codification and use of information: decisions toward R2S attributes

During early design phases, traditional methods for R2S were only performed with information and data from models about the definitive design. Earlier designs were evaluated with the support of other methods such as tolerance chains and confidence-based evaluations. There were inconsistencies between decision-making and the reuse of decision rationale in subsequent designs: although designers had clear reasons for rejecting alternatives, they were not able to pinpoint the mechanisms of failure. For this reason, a knowledge-based tool was developed and verified.

The issues considered for developing the design tool include (a) scattered information for locating and assessing R2S attributes across several design documents about solution alternatives, and (b) a lack of coherence between reasons for rejection of alternatives and design feedback reusing the rationale of decisions about R2S attributes.

Current methods for R2S in use during early design stages focus either on the generation of overviews about requirements, or on detailed parametric assessments. Such was the case, for instance, with SETx matrices – such as found in (Sobek, Ward, & Liker, 1999) – giving an overview of how alternatives were seen to satisfy different design requirements, and with tolerance stacking tables (Chase & Parkinson, 1991) applied to several designs of solution alternatives. However, none of these contained complete information regarding functional shortcomings in the product and their implications for R2S attributes.

As found in the project documentation, this caused the scattering of relevant information across several design documents under consideration for judgment about solution alternatives. This generated difficulties in assessing R2S attributes across several product architectures on which solution alternatives were being developed, where reasons to reject alternatives were known with regard to the undesired outcome, but not much was known about the mechanism of failure. This caused incoherence between statements rejecting bad alternatives and feedback towards new ones, as seen in Paper VI.

To ensure the integration of source information on R2S evaluations, as well as the coherence between evaluations and feedback to new designs, other propositions explore intuitive relationships between design tasks (Table 30). Methods working in design reviews such as DRBFM (Shimizu, Imagawa, & Noguchi, 2003; Otsuka, Takiguchi, Shimizu, & Mutoh, 2011), triplets for iteration during the generation of working principles (Kroll & Shihmanter, 2011), and P-strategies based on robustness patents (Jugulum & Frey, 2007), elicit problem-solving knowledge by pointing out current issues and ways of solving them.

Table 30 – Comparison to other studies on codification and use of information (from Paper VI)

Industry/ref.	**Design tool** [this study]	**DRBFM** [Otsuka et al., 2011]	**Triplets** [Kroll & Shihmanter, 2011]	**P- strategies** [Jugulum & Frey, 2010]
Type of product	Medical device	Automotive	Hydraulic systems	Automotive, aerospace
Size, scope, no. parts	Small, whole product n x 10^1	Medium, subsystem, n x 10^2	Medium, whole product, n x 10^2	Small, components, n x 10^1
Complexity	Medium	High	High	Medium
Damages from design flaw at use	EUR x 10^7	EUR x 10^6	EUR x 10^4	EUR x 10^6
Focus area	Eng. design, knowledge mgmt.	Eng. Design, DFx	Eng. design, knowledge mgmt	Eng. design, robust design
Methodology	Prescriptive study and descriptive II	Descriptive study II, industry practice	Prescriptive study	Prescriptive study
Design phase	Concept design: evaluation of alternatives	Detailed design, engineering change	Concept design, generation of principles	Embodiment design, dimensioning and layout
Source data	History of failure and benefit attributes of alternatives in early design phases of an R&D project	Test case from industry using prototype, assembly drawings and design data	Test case in laboratory using manufactured product and reverse engineering	Patent database, product examples from drawings, claims and text from individual patent requisitions
Type of method	Keyword-based fields in graphic card layout	FMEA-like fields in spreadsheet layout	Taxonomy keywords in form layout	Link-branch-variable from flow diagram
Source of information	Assembly cutaways, augmented with icons	Assembly drawings, component hierarchies	Freehand sketches of product	Patent drawings, claims
Verification setting	Simulation task with industry practitioners	Actual practice in academia and industry	Simulation example with academic work	Simulation example with patent search
Authentication of performance	Compares results from users of the method and those from original project in industry	Compares between practitioners using the method and others using FMEA	Prescriptive case study with supervisor reviewing output from primary author	Document sampling from patent files and statistical keyword processing from search

The methods shown in Table 30 focus on different scopes of activity during the design process: DRBFM can be applied at a single subsystem throughout several design phases, evolving in detail (Shimizu, Otsuka, & Noguchi, 2007); concept evaluation triplets are based upon sequential tasks of a methodology to generate working principles (Kroll & Shihmanter, 2011) from functional parameters, embodied into function carriers (Kroll, Condoor, & Jansson, 2001). P-strategies reproduce the thought process of robust design (Phadke, 1989) to define courses of action for fine-tuning parameters in working principles (Jugulum & Frey, 2007).

The methods shown apply different approaches to R2S attributes, departing from information on current designs to choose and prioritize improvements, or making general prescriptions of strategies to handle parameters with design examples. Methods considering R2S in early design phases must present a suitable range of design characteristics influencing R2S attributes, and must ensure coherence between evaluations and feedback if the repetition of problems is to be avoided. These requirements must also take into account the fact that evaluations consider several alternatives at a time and mitigate the variational complexity of several architectures. The techniques immediately reuse the knowledge generated during their execution to improve R2S attributes:

- Sets of logical component connections and functional requirements are considered to establish the scope of review in the evaluation of early designs;
- Components included in this scope are characterized by their functions and the interfaces working to satisfy the expected behaviour; and
- Inconsistencies against expected performance of working principles are characterized in relation to component combinations in product designs.

The approach to strategic principles suggested by P-strategies determines a specific interpretation of design characteristics within the model and the terminology of robust design techniques (Jugulum & Frey, 2007). The use of triplets in evaluation of design characteristics helps ensure internal coherence among parameters in working principles, without considering disturbances to their performance (Kroll & Shihmanter, 2011). Design review methods such as DRBFM help to address issues in a system scope upon interferences from design changes and environment (Shimizu, Imagawa, & Noguchi, 2003).

According to designers, the authentication of information and the weight of expert opinion must be allowed for when considering the communication workflow in the industrial environment. As with Paper VI, the design tool was developed with language based upon proven terminology, and for use at a wider design scope than DRBFM while using a similar protocol. The characterization of R2S attributes in records with design characteristics required more stamina from designers, as the tool was heavier in reasoning and required more discussions. Positive results were obtained, as designers selected the best design and used its records as references for improvements that were converging towards the principle solution.

5.1.4. About knowledge, language and confidence in early design stages

This research assesses the shortfalls in current methods and practice of concept development, and proposes the use of knowledge support in response to those issues in early design stages. The approach of design records combines the use of approaches typical in methods for R2S with a knowledge management approach to gain maximum benefit from the information packages under consideration. This research work contributes to understanding the types of design information that describe attributes of technical performance in early design phases.

In addition to this, knowledge was gained about the availability of such knowledge types depending on the level of detail to which the design is developed. While information about *function* and *product* types can be defined right at the onset of the design process, early phases generate no information about their observed modes of failure and respective consequences. The *issues* causing such failures are also unknown, and emerge as the design being developed is run against likely conditions of use. This indicates a lack of knowledge about how alternatives perform when confronted with use conditions.

In addition to this, designers usually refer to functions of the design as component names (Ahmed & Wallace, 2003), and a variety of working principles is used in several alternatives through concept development. The variation in functional interfaces and changes in performance parameters makes it difficult to compare performance across alternatives, which also makes it problematic to identify and locate flaws in the design. Hence, another contribution from this research regards the discovery of the influence of product architectures and their descriptions to the identification of R2S attributes during early design phases.

To address this, the design tool based upon card-like records was developed from generic categories in the R2S taxonomy, whose terms correspond to fields with language and modelling representing design issues. The use simulation of the tool elicited knowledge about a specific type of product from designers, who used their own knowledge as criteria to examine issues, and avert the repetition of failure modes. By reducing the ambiguity from variety and complexity in alternatives, the design tool helped avoid the reuse of failed working principles to proceed towards a principle solution.

Some effort was required to interpret function and working principle definitions that were new to them, but they proposed successful countermeasures indicating how failure modes would be averted. Hence, the R2S taxonomy helped to mitigate the influence of configuration ambiguity on design decisions and improved the reuse of decision rationale in form of protective measures.

5.2. Contributions of this project to industry

This research has engaged in supporting concept development with fundamentals from systematic methods for R2S attributes in engineering design, and in augmenting these with knowledge-based support. While current methods to R2S require years of design expertise, knowledge-based approaches are envisioned to leverage available knowledge to reduce the risk and cost of innovative development projects in industry.

5.2.1. Design records in a single decision-making routine

Analyses on the use simulation of the design tool showed encouraging results from the reuse of knowledge about R2S attributes in decisions and suggestions for improvement. Industry stands to benefit from the use of records to prepare and mediate design review processes and decision routines. The set of alternatives evaluated during the use simulation of the design tool was developed in the period of 12 months in the original project from the industrial case. Designers effectively discarded all early alternatives that contained significantly flawed working principles and maintained those with reasonable combination of failures and benefits.

Moreover, the alternative with the best combination of issues between failures and benefits was chosen for further development. Solutions for outstanding issues proposed by designers to improve the best alternative were successfully compared with working principles found in the principle solution from the original project. These involved component design suggestions that were also similar to the definitive mechanism design generated from the original project in the industrial case after 36 months of concept development.

5.2.2. Design records evolve to other industry segments

The approach using design records can be successfully applied in companies working with concept development processes involving several alternatives. The fields used in the design tool were generated with support of the generic categories in R2S taxonomy, which was developed from empirical research in industry (Ahmed, 2005). This approach can be verified and applied in other industry segments outside the mechanical domain, with the incorporation of product-specific issues. The tool also benefits from recording incidents with designs from past projects, which can then be applied by analogy in current designs.

This generates a positive effect on the convergence from several alternatives into the solution principle, which can be managed by defining how many times design records will be used during concept development. The approach of records also allows developing a repository of failures and benefits from past projects, which can be used by analogy in current designs to generate creative adaptations and anticipate design issues in alternatives being developed.

5.2.3. Flexibility and scalability with generic fundamentals

As it is based in records, the design tool developed in this thesis is a flexible and scalable approach to ensuring the generation of effective designs for new products. The R2S taxonomy incorporates fundamentals from traditional approaches to reliability and safety, and the modelling approach to information on records creates a flexible platform for describing design issues. This is enabled by the use of generic fundamentals:

- The relationships between fields in design records that follow the terms in the R2S taxonomy along the visual organization of records, and
- The models representing each category of the taxonomy in the visual arrangement of the card-like records in the design tool.

Relationships between categories are described in the records of the design tool in two parts. The first aims to locate design issues within the system being developed by part-of relationships in *function > product > issue*; and the second defines design issues by cause-effect relationships in *issue > failure/benefit > event > consequence*. Along with the overview of the configuration affected, the terms can be applied irrespective of the solution alternative. Records can also carry information to authenticate their source and validity, so as to ensure the level of confidence needed to implement directions based on their use.

5.3. Limitations

This project consisted of an exercise looking for unexplored opportunities whose path was largely unknown at the outset of this research. This section reflects on the limitations of this process of discovery considering the steps on which this project was developed.

5.3.1. Definition and selection of case studies

The case studies were largely defined in accordance with the available network of contacts that enabled the acquisition of products/information and the use of facilities to carry out the activities. The findings of the pilot case study were shown to apply to other products: the washing machine study was verified by carrying out a similar analysis of the design of a centrifugal fertilizer spreader (Marini, Restrepo, & Ahmed-Kristensen, 2009), which yielded similar findings to the washing machine case study.

However, the industrial case about the insulin pen significantly influences this research, as circumstances of the corporate environment and the practices used determine the findings from the descriptive study. The small size of the product determines the affordability of physical prototypes and their testing during early design. This contrasts with other applications such as wind turbines and aircraft where such a concept development practice is restricted to the scope of the subsystem.

In addition to that, strict regulations in the medical industry determine the degree to which alternative designs need to be developed before receiving the go-ahead for manufacturing development.

5.3.2. Methodology

Specific factors related to the choice of research methodology and its implementation affect the fidelity between results from this research and the real context. The longitudinal study in the industrial case was carried out during 24 months, starting six months after the principle solution – the definitive design – was generated and approved inside the company. Other limitations apply to the selected methodology as they determine the assumptions for the development of the record-based design tool from the industrial case study:

- Inherent bias on the part of the participants and the researcher towards the information on the product being developed,
- Observations could only be carried out following ongoing and detailed risk analyses in which the principle solution was already defined, and
- In-depth knowledge of the product was a precondition of making a comparison among alternatives, as there was no high-level framework to define the system.

These circumstances determined that a longitudinal and retrospective study was selected to follow concept development activities, which were carried out for 36 months, regarding the development of the solution principle for the insulin injection device. The lack of synchronism between the design activity and the industrial case determined the limited feedback from the application of the design tool to the same project in the partner company.

5.3.3. Verification of findings

The approach of design records that was developed as a prescriptive approach from this research was validated only as proof-of-concept in a use simulation routine of decision-making during concept development. The results from the industrial case were discussed with the participants of the use simulation to collect their feedback, and then compared to current knowledge from literature. The feedback relationship from the results of validating the tool towards the original project is limited by the fact that actual activities of concept development had already finished by the time the descriptive study was started.

At the time of the conclusion of the descriptive study, detailed design activities were underway and design records could not possibly address the issues under consideration. To develop the design tool towards an industry-ready package with all due improvements such as authentication of records and communication among design teams, a long-term commitment to embodying and testing the tool was required. As there was no other project with such scale in the company, no further activity was executed to further develop the tool.

Such activities were not feasible within the timeframe of this research, as concept development in the original industry project lasted at least as long as a whole Ph.D. study. Besides, no other similar projects were carried out at the company during the time of study.

5.4. Conclusions

This chapter discussed the contributions of this project to research and to industry. Contributions to research were discussed in terms of the problems in the design activity addressed by this research, linking the factors of available knowledge, suitable language and confidence in favourable outcomes, as a supportive thread to evolving considerations on technical risk to R2S attributes. Contributions to industry were discussed in the form of the results obtained from the second descriptive study, their evolution to other industry segments, and their flexibility in considering more complex systems in the approach.

This means unnecessary concept development work can be avoided, provided that domain-specific characteristics of language and communication are addressed. The approach is also scalable for use with the concept development of more complex systems. The limitations of this research were addressed in view of the influence of the case studies it performed, going through characteristics of the methodology, and concluding with the circumstances of verification and validation. The circumstances of the project investigated during the industrial case study influenced the conclusion on the repetition of flawed working principles.

At the same time, the methodology employed could not address ongoing developments in the project, and the verification was not carried out on a fully implemented form of the tool. Our observations were then restricted to the proof-of-concept verification, carried out in a paper version. The limitation to the practical contributions stems largely from the combination of research practice within a limited time span and a topic whose investigation requires long-term commitment for meaningful results to arise.

Chapter 6 - Conclusion

This chapter gives a summary of the research project and a description of the main areas of contribution, including suggestions for future research. The problem of this research is contextualized within the need to ensure **that there will be feasible alternatives** to the **principle solution** of a product during concept design and development. To achieve effective performance in respect to design specifications, the final product from concept design must satisfy functional requirements by working in a manner that is:

- Insensitive to disturbances within the construction or from the environment that may prevent it from performing optimally;,
- Protected from failures stemming from component degradation or lifecycle conditions that may prevent it from working when needed; and
- Safe to people and the environment by avoiding conditions that induce hazards during operation and over the lifecycle.

Innovative projects with early design phases in their scope become therefore prone to design flaws, plus cost and time overruns, due to the unnecessary reuse of failed working principles. The research presented in this thesis was motivated by the fact that current methods for robustness, reliability and safety (R2S) were failing to reduce such issues at the time designers were generating and evaluating solution alternatives. Hence the need to develop support to dealing with R2S attributes, in order to reduce iterations resulting from the reuse of flawed principles in solution alternatives.

This research consisted of an investigative effort to address the following aim, guided by the research questions shown in Table 31.

Table 31 – Aim of this research, and research questions

Aim of this research: **To improve the use of information about robustness, reliability and safety (R2S) in identifying for/against characteristics of solution alternatives during early design phases**			
What information about product design do current methods for R2S need in order to generate information about R2S in a product?	**How does information about R2S from concept design influence practice to improve R2S on solution alternatives?**	**How should one model information about R2S in solution alternatives for methods that elicit practice to improve R2S during concept design?**	**How does the proposed model of information about R2S elicit practice to improve R2S during concept design from a method for R2S?**

6.1. Findings to the research questions

This section discusses the findings to the research questions on the basis of the investigative effort carried out during the research project. Each research question is presented in its intended context and the environment from which data was collected, to gather with previous and new findings. The application of current R2S methods does little to benefit the synthesis and choice of solutions, as methods require product designs to be reasonably detailed regarding materials, components and their assembly. Hence, they become too expensive to be undertaken during conceptual design, with several designs developed at the same time.

6.1.1. What information about product design do current methods for R2S need to generate information about R2S in a product?

The literature discussed the feasibility of current methods for R2S attributes and found recommendations for their use in later design phases (Glossop, Ioannides, & Gould, 2005) and a lack of examples of their use in conceptual design problems (Andersson, 1997). A preliminary pilot case was carried out to investigate this question further: current R2S methods were conducted to identify design issues in a washing machine. Although the methods could be used to frame problems, they could not be completed with the information or time available during early phases (Marini, Restrepo, & Ahmed-Kristensen, 2010).

A preliminary definition was also made of the types of design information required by R2S methods. Departing from the empirical EDIT taxonomy (Ahmed, 2005), two new types of information (*failure mode > event*) were identified to address design issues in R2S attributes. One resulted from reviews of other classifications of failure – such as (Bloch & Geitner, 1990) – and the other was extracted from the data upon its use in the methods. In addition, it was found that issues are difficult to clarify in projects that involve original designs or adaptive designs with significant modifications.

Prior knowledge about the use of a product makes significant difference in adaptive designs, which facilitates understanding of how a product or system is intended to operate. Knowledge of the technology without an understanding of the purpose of the product may be subject to changes of operational and/or use conditions and hence is not stable knowledge. The scenarios that were identified in paper II depend on the availability of prior knowledge about the product and/or its use. The lack of similar past solutions will require a discovery process to identify the missing links between information characterizing product performance.

6.1.2. How does information about R2S from concept design influence practice to improve R2S on solution alternatives?

The literature reviewed involved a limited understanding of how current methods for R2S attributes were effectively applied in industry. To this end, an industrial case was performed to find out how concept development is performed with these attributes in mind. The case company was developing a novel insulin injection pen that forced designers to rethink the whole product concept, including the internal mechanism. A longitudinal case study was performed to investigate 36 months of design activities for concept development, with the observation of two meetings during the later risk management process.

Evaluations in early design phases were found to be more difficult due to complexity and variety in product architectures. These were also found as having limited effectiveness in pinpointing the causes of failure. During the industrial case, component names were found as references to product functions, and used differently in several solution alternatives. This kind of ambiguity, along with the complexity of mechanical interfaces inside the insulin pen, was identified to be the cause of reusing flawed working principles from earlier solution alternatives (Marini, Ahmed-Kristensen, & Restrepo, 2011).

The lack of feasible options was a significant problem, as it was difficult to learn of and mitigate prior failures. Feedback from flawed solution alternatives was incoherent with reasons for prior decisions and focused on components rather than on functions and their parameters, especially after partial milestones. Safety issues in early solution alternatives were overlooked, and hence further alternatives manifested significant problems in this regard. The build-up of several similar designs mitigated the problem by working as a learning-by-doing mechanism, but it did not help to generate more feasible options.

All of this seemed affordable for a small device from which several prototypes can be built. However, this attitude incurs significant technical risk, as there were only two alternatives that could be expected to meet the required criteria. Complex regulations in the medical industry dictate a thorough consideration of R2S attributes prior to production. Overlooking these at concept development becomes quite an expensive business in regard to the changes needed. The lack of feasible options during concept development may also force a flawed design through detailed engineering, whose corrections will then be quite expensive.

6.1.3. How to model information about R2S in alternatives for methods that elicit practice to improve R2S during concept design?

The results from the industrial case motivated and formed the basis for the development of support to dealing with R2S attributes during early design phases. Current methods for R2S become either too cumbersome to help in solving such specific issues or too intolerant of the ambiguity among solution alternatives to mitigate such problems. For this reason, an approach based upon the use of the R2S taxonomy developed during the pilot case was elected to support the evaluation of solution alternatives. The characterization of design problems throughout the industrial case led to the inclusion of a consequence category in the taxonomy.

The prescriptive study included the recognition of critical tasks to apply the approach, as with the results of the prior question. Through partial milestones and reviews, decision-making and feedback were seen as critical points in need of support during concept development. An approach to rendering information on failures and benefits from design alternatives was then developed. The approach was embodied with the R2S taxonomy, which was implemented in several fields to be visualized in a single field view over a card-like graphic layout.

Information on R2S attributes was conveyed in the form of individual design records that carried the following elements: an overview picture representing the design issue, with icons representing its location and characteristics; fields characterizing the location of the issue in the system (*product > function > issue*); and fields characterizing its effect on the performance of the alternative (*failure/benefit > event > consequence*). The failure/benefit option enabled the addition of issues with positive effect as well as of issues with negative effect.

The design tool ensured that designers were not forced to predict problems, but instead added information relevant to their decision on the best alternative and the issues in need of solution. Records of solution alternatives were generated for evaluation by designers towards selecting the best feasible alternatives against R2S attributes, and for serving as a reference on outstanding issues for solution by the use of new records where designers suggested countermeasures. These were developed as response to solving issues in failure records.

These records in the tool were intended for designers to propose solutions, in the same way they thought about failure and benefit records. The information designers were to add in countermeasure records was intended to guide further effort in implementing the intended solutions.

6.1.4. How does the proposed model of information about R2S support practice to improve R2S during concept design?

Considering the results from the industrial case, the approach based on the R2S taxonomy needs to satisfy the following requirements: first, that causes of failure are effectively pinpointed; second, that R2S issues are not overlooked during the decision process; third, that there is commitment to feasible developments; and fourth, that outstanding issues are mitigated. The use of records aims at reproducing the learning process from current practice, based upon evidence of failures and benefits.

Records were designed to convey information about the mechanism of failure, the working principle that manifests the failure, the function affected by the failure and its location in the system. While it is necessary to improve understanding of the meaning of functions and working principles in current practice, the definition of different levels for locating the failure helped the identification of issues (shortcomings in the design/prototype) and their effects on the system that were well understood. R2S issues were not overlooked at all by participants in the simulation task, as their effects were made explicit by the use of the records.

With this support, designers were able to tap into their own knowledge of the implications and make effective decisions based on their own understanding of the records. During the verification of the tool, designers reached the best two alternatives and proceeded with the simulation task by using the best one. This was explained on the basis of the following characteristics of the winning solutions: the relationship between the number of failures and the number of benefits was favourable; the outstanding issues were deemed solvable; and the outstanding issues seen to share common features (for instance, two records carried similar issues on nearby components).

Furthermore, outstanding issues were successfully mitigated by the use of countermeasure records to elicit designers' proposals for addressing the outstanding problems. The written definition of the issues, along with their representation in the alternative model, was found to support designers generating design changes and new components. The propositions effectively mitigated the outstanding problems as employed in the chosen solution principle, with direct reference to the original records used in the decision process. The use of records in the simulation task satisfies this question, as failed working principles were definitely avoided.

6.2. Contributions from this research

This section discusses the contributions from this research to the fields of literature. Each field is presented according to the contributions from the findings of this research. Final considerations reflect on the current state of knowledge and future developments.

6.2.1. Contributions to systematic methods for R2S

This research has contributed to better understanding of how current methods support this and their limitations of use in early design phases, through investigating the information requirement of such methods and the scenarios under which it is available. Logical-hierarchic strategies as found in FMECA, FTA and HAZOP can be used to frame the problem, but cannot be completed during early design (Marini, Restrepo, & Ahmed-Kristensen, 2010). Current methods do not yield significant gain as they focus on component details, and thorough understanding of the design is not available at early design stages.

This project has also generated understanding about practices currently used in industry to assess R2S attributes during early design phases, through a deep longitudinal study that investigated the development of 20 concepts through 36 months. All design alternatives were developed by reusing and adapting similar working principles to different embodiment layouts. However, the repetition of failures in design alternatives due to the reuse of flawed working principles was a major reason contributing towards project delays. This was found to be due to difficulties in identifying the source of failures in alternatives as tided to working principles.

6.2.2. Contributions to knowledge management in engineering and design

This research contributed for better communication of design issues about R2S attributes by proposing a design tool based upon card-like records. Through the use generic information categories, a taxonomy of design characteristics was created to generate and index descriptions of R2S attributes in early designs, and implemented in the design tool. Individual records use *function > product > issue* categories from EDIT (Ahmed, 2005) to locate individual design issues and to identify the product function that is affected.

The use of generic taxonomies makes language more flexible in representing the objects of interest, as long as the language used (the type of model, for instance) communicates the attributes properly. Units of explicit knowledge can be used to elicit implicit and tacit knowledge with the support of scenarios applied to taxonomies. In this context, taxonomies operate implicit knowledge that can be generically understood in their use through their relative graphic positioning around the representation of the alternative.

6.3. Further work

This section discusses further work that can be carried out from the results of this investigative effort. Each follow-up alternative is hereby presented within the conditions needed for implementation.

6.3.1. Implementation of design record tool

A user interface mock-up of the design record tool, whose functionality has undergone preliminary evaluation, was developed for this research. A further step would be to develop the mock-up fully into database software that can access resources from project databases in the company to generate the records.

6.3.2. Expansion to other industry sectors

This research has carried out a thorough investigation of concept development in the sector of medical devices. Another path following on from this topic would be to expand the evaluation of design records as knowledge support for R2S issues in other industry sectors with focus on capital goods, such as oil drilling and production equipment, energy generation machinery and transportation systems.

6.3.3. Verification of long-term performance

That this research engaged in the development of a design record tool with a prescriptive study and a single-decision routine was mainly due to the time constraints on this project. Further efforts should involve the use of design records in a series of decision-making routines over the medium and long-term to verify effectively their effect on design practice.

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Contributions – Papers I to VI

Paper I

Co-writers:	Marini, Vinicius K; Restrepo, J.; Ahmed-Kristensen, S.
Title:	**Evaluation of information requirements of reliability methods in engineering design**
Destination:	International Design Conference, DESIGN 2010, University of Zagreb and The Design Society (published)
Contribution to thesis	The paper contributes to the thesis by identifying the difficulties to use current R2S methods in early design phases – as it is not possible to complete their queries – and directs further research efforts to identifying other possible ways in which R2S attributes could be treated in industrial practice of early design phases.

Paper II

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**Information requirements of current methods for robustness, reliability and safety during early design phases**
Destination:	Quality and Reliability Engineering International, Wiley, ISSN 1099-1638 (submitted)
Contribution to thesis	The paper contributes to the thesis by confirming the feasibility of the partial use of current R2S methods in early design phases, and clarifying the design situations (adaptive, innovative) where relevant information is absent. This paper contributes to the thesis in relation to the development of ways of revealing mechanisms of failure with working principles during early design phases.

Paper III

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S., Restrepo, J.
Title:	**Influence of design evaluations on decision-making and feedback during concept development**
Destination:	International Conference on Engineering Design, ICED 11 Technical University of Denmark, The Design Society (published)
Contribution to thesis	The paper contributes to the thesis in providing evidence of the lack of clarity regarding information about R2S attributes in early design phases, and in pointing out the consequences of reusing failed working principles – leading to the rejection of several alternatives in the process. This paper contributes to the thesis in relation to the need of support during early design phases.

Paper IV

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**Decision-making and feedback as foci for knowledge-based strategies supporting concept development**
Destination:	International Design Conference, DESIGN 2010, University of Zagreb and The Design Society (published)
Contribution to thesis	The paper contributes to the thesis by investigating the use of set-based development to address the development of alternatives in the whole functional scope during early design phases. It highlighted the influence of functional complexity that makes the reuse of failed working principles more likely during early design phases. This paper contributes to the thesis by defining the focus of developing support to assist the feasibility of solution alternatives during early design stages.

Paper V

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**The current use of engineering knowledge for evaluation and selection of solution alternatives during early design phases**
Destination:	Research in Engineering Design, Springer, ISSN 1435-6066 (submitted)
Contribution to thesis	The paper contributes to the thesis regarding the current use of knowledge as a result of complexity in solution alternatives and in the protocols of current R2S methods. This complexity makes methods for R2S prone to error, because there are insufficient references about failure mechanisms on working principles and their parameters.

Paper VI

Co-writers:	Marini, Vinicius K; Ahmed-Kristensen, S.
Title:	**Requirements, development and verification of a design tool to codify engineering knowledge about attributes for failure and success of solution alternatives during early design phases**
Destination:	Journal of Engineering Design, Taylor & Francis, ISSN 1466-1837 (submitted)
Contribution to thesis	The paper contributes to the thesis by asserting requirements and conditions for the development of knowledge-based support for early design phases. A card-like approach, which yields information about alternatives regarding R2S attributes used in review-selection-feedback routines, has avoided the reuse of failed working principles.

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EVALUATION OF INFORMATION REQUIREMENTS OF RELIABILITY METHODS IN ENGINEERING DESIGN

V. K. Marini, J. Restrepo and S. Ahmed

Keywords: Robustness & reliability, assessment methods, information requirements

1. Introduction

Product designs can be evaluated in terms of their reliability and robustness (R&R) by quantitative and qualitative methods. The former, such as structural reliability [1] and statistical approaches [2], require significant amount of design data; whilst the latter, like Failure Mode and Effects Analysis [3], require design expertise.

With more room to decision-making being available during early phases of product development [4], qualitative approaches better support design decisions where they are most cost-effective. In our view, qualitative methods fit better to early design stages; they allow designers to avoid failure early rather than spend time and effort correcting it later, because they focus on applying engineering judgment.

In this context, there is need to unfold knowledge required by different R&R assessment methods and compare it to available information during conceptual design, so that:

- There is better guidance to look for product information on early R&R assessments;
- Advantage is taken of available information at early design stages; and,
- Designers have better support to evaluate design R&R by conceptual design.

This paper aims to characterize the information needed to perform selected R&R methods, and verify their applicability to early design stages. This paper contributes to the field of design methods with the following results: it diagnoses the availability of design information to using R&R methods through the design process; and, verifies the feasibility of R&R methods for application in early design stages.

2. Robustness and Information Taxonomies

2.1 Reliability

Reliability reflects the ability of a system to perform its task with adequate availability. Current methods to design for reliability (DFR) take reliability as a function of failure probability on operation, looking to provide means to decrease that probability. The following methods meet these criteria:

1. FMEA/FMECA: [3];
2. HAZOP: [5];
3. FTA: [6];
4. ETA: Event Tree Analysis [7]
5. Safety-barrier diagrams [8],

DFR methods enable designers to use their knowledge and expertise by prompting them to think about reliability in a systematic way [9], enabling designers to prioritize critical design issues. Many of these methods rely on complex data, and significant expert input. Nevertheless, using them allows designers to take advantage of their knowledge to improve product design on safety and reliability.

2.2 Robustness

Robustness is understood as the insensitivity of a system to uncontrollable conditions such as in operating conditions, manufacturing variability, and throughout the product lifecycle. There are methods for robustness improvement, prompting designers to think about how deviations take place and on ways of controlling them. Methods with such objectives are:

6. Axiomatic design [10];
7. Quality engineering/Robust design [11] and,
8. Parameter-based decision method [12].

While axiomatic design aims to minimize coupling between functional requirements and design parameters, robust design looks to determine and minimize influence from disturbances in performance (signal-to-noise ratio) using experiments. The decision method joins robust design and axiomatic design by combining signal-to-noise ratio with assessment of parameter independence.

2.3 Design models and taxonomies

Design models and taxonomies help decompose, separate and structure the design problem, simplifying it into less complex issues. They are often empirically derived because they depend on specialist language, either from experience or research. These models are explained in three tracks:

- Techniques for function and system modelling;
- Classifications of system design entities and design process entities; and,
- Specific classifications of R&R engineering knowledge:

Functional modelling decomposes an overall purpose into chains of energy, material and information flows [13]. Organ modelling describes components and their links in two ways: by sketches [14]; or by flow-charts [15]. The functional basis provides a standard vocabulary [16] to be used in function structures. These methods aim to separate and structure design issues in manageable sets.

A classification of mechanical connections, also in [13], supports proceeding with embodiment design while the links between components are yet to be fully understood. An integrated taxonomy [17] uses an ontological approach to describe engineering design activities and their context. These propositions support structured descriptions to design relationships both in product as in process, respectively.

Other taxonomies of mechanical failure come basically from accumulated knowledge through research and experience [18, 19], describing factors and processes that cause failure. Means to achieve robustness on design principles [20] are described from patent search. Those taxonomies show R&R information depending on system behaviour and control strategies used by designers in controlling it.

3 Evaluation of R&R methods

3.1 DFR applicability to early design

DFR methods have been formerly assessed on their applicability to different design stages. One report reviews how DFR methods' support risk management [21]. Other review of DFR methods on hazard identification provides a more general perspective [22]. They recommend DFR methods throughout the design process, but question their effectiveness to early stages.

According to both sources, DFR methods require extensive information and knowledge on the design under development. Other issues to using DFR methods are: (a) they may not cover all issues within a single analysis; (b) they consume significant time and require expert input; and, (c) many of them have limited reach within human factors.

3.2 Robustness on early phases

Original robustness methods, such as [23], require both significant data and rigorous formalism. to be used effectively. No prior assessment exists on the applicability of original or adapted robustness methods to concept development such as with DFR methods. Nevertheless, there are relevant cases where robustness fundamentals are demonstrated to be applicable.

Design strategies are proposed to avoid failure modes in concept design, considering design parameters and acceptable ranges [24]. An approach to conceptual design retains robustness fundamentals specifically adapted to the design synthesis process [25]. These examples show there is room for improvements in the area.

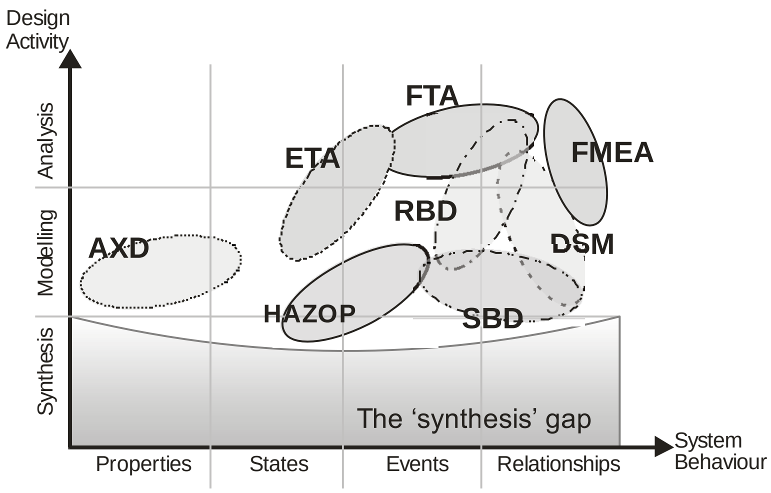
3.3 Our preliminary evaluation of R&R methods

The suitability of R&R methods to early phases has been diagnosed in different extents. DFR methods were shown to be assessed on their applicability to different stages of the design process; and, early robustness methods were demonstrated with mock examples. That does not bring meaningful answers to how R&R determine requirements on necessary product design information.

For that reason, a preliminary comparison of R&R methods has been performed. The methods are compared in two metrics:

- Contribution of R&R methods to create or describe design characteristics, on design activity progress (synthesis, modeling and analysis); and,
- Characterization of design information on system behaviour, on progressive level of detail (properties, states, events and relationships).

This evaluation considers current instructions and prescriptions to use R&R methods in design tasks, as stated in our references. The graph in Figure 1 shows our assessment of how methods' prescriptions cover design activity and design information.



AXD	Axiomatic design [10]
DSM	Design Structure Matrix [26]
ETA	Event Tree Analysis [7]
FTA	Fault Tree Analysis [6]
FMEA	Failure Mode and Effects Analysis [3]
HAZOP	Hazard and Operability Studies [5]
RBD	Quality Engineering/Robust Design [11]
SBD	Safety-barrier diagrams [8]

Figure 1 – Evaluation of design information output from R&R methods

The evaluation on output to design activities clarified our grasp on the lack of R&R methods whose output can directly support design synthesis.

Few methods, such as HAZOP and Safety-barrier diagrams, get close to directly orienting design synthesis to mitigate risks. On other R&R methods – DSM [26] has been considered due to its wide application on product development – synthesis knowledge come as result from significant effort on modelling and analysing the system under development.

3.4 The synthesis gap of R&R methods

The preliminary evaluation has shown there is a gap in how current R&R methods directly lend support to design synthesis.– see the ‘synthesis’ gap in the figure. Parameter-based approaches were presented as ways forward by literature, as commented on item 3.2: However, they direct design responses to disturbances and do not directly refer to why design problems should be corrected.

The current assessment shows an opportunity window for methods directly addressing design R&R showing *why and how* to avoid failure.

4. Research method

This work is carried out as a partial descriptive study within a design research framework [27]. The strategy to collect the data and gather insight follows a case study framework [28]. With the objective of extracting further research criteria and preliminary insight on the problem, it is to be considered as a pilot case study. The research methods used for extracting the information from the context were selected among the following alternatives: literature review; document analyses; and action research.

Literature review created awareness on current R&R methods and helped evaluate which should be selected. It also supported the preliminary analysis to choose the methods to be performed on the following criteria: the insight they provide on design risks; and, the extent of their application in industry. Hence, three methods were selected: (a) FTA; (b) FMEA; and, (c) HAZOP.

Then the product under analysis is defined with the following criteria: it is readily available; its main functions are mechanical; and, descriptions can be quickly found. For those reasons, a washing machine was selected. It uses action research on the ground of active participation of the researcher in gathering documentation and carrying out the assessments with R&R methods.

The product evolution methodology [29], is used as framework for this case, where the approach to followed the Reverse Engineering stage. The method prescribes steps for doing product analysis, whose result will feed the R&R methods chosen. Complementing that methodology, the following procedures were performed:

- Disassembling the product and getting technical data;
- Modelling the product in functions and organs;
- Considering the issues to reliability and robustness;
- Performing FTA, FMEA and HAZOP methods;
- Documenting the information used in the methods;
- Classifying the required information, related to design models; and,
- Comparing the methods on their applicability to early design phases.

The documentation procedure includes acquiring product references from: product disassembly; and, use and maintenance prescriptions by manufacturers and third-party support services. The assessments involved using function and product modelling approaches [13, 14, 30] to describe the system, find out the prominent design issues and carry out the R&R analyses with the chosen methods.

The analyses were documented so that to evaluate R&R methods on their information requirements. In this study, these are assigned to information fields from the methods and assessed on the detail level they require, following information characteristics of different stages in the design process [13].

5. Results

A review of R&R methods supported the choice of three methods for a case study with a washing machine. The methods were applied in describing a design issue and evaluating the information requirements for using them. The results are shown in a retrospective order.

5.1 Information structures of R&R methods

The objective of this item is to grasp the information requests of the selected R&R methods, and what input engineers have to provide in order attend to each of these requests. To achieve that goal, the selected R&R methods are decomposed into information structures that separate and explicit their information units. Each method is then described on its units and their classification, as in Figure 3.

Information units from FTA are individualized following the symbol notation and the associated meanings. The division is made on symbol groups, as shown in the figure: FTA gates, top and intermediate events, and primary events. Information is individualized following sets of symbols: primary events follow the types prescribed in [6] as found in the problem: basic event (quantified), external event (certain) and conditional event (condition on gate).

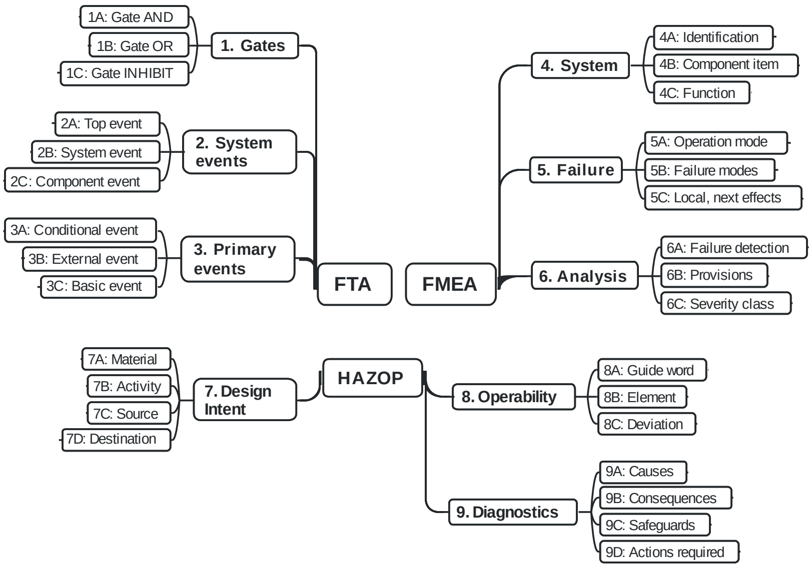


Figure 2 – Information hierarchies and units of R&R methods: FTA, FMEA and HAZOP

Information units from FMEA are individualized following the column fields from its spreadsheet format. The group division is made considering the focus of column fields through the spreadsheet: system, failure and analysis. Information is individualized following column designation: system information follows part identification, component item and function, as shown in [3]: the system field is composed by identification, component item and function.

HAZOP information units are derived in similar way to FMEA's. The group division is done by separating information groups from sheet designation and assessment columns: design intent, operability and diagnostics. Information units are derived from these scopes following the spreadsheet. [5]: operability groups guide word, element and deviation columns.

The resulting hierarchies help separating specific information from similar types, and assigning information units to their corresponding design information. The information units are individualized and coded to be assigned to design information they require and assessed on how complex that information is.

5.2 System models and information to R&R methods

Following the research approach, system models were created to represent different detail levels of an engineering problem in the design of the washing machine. Consequences to product functions were related to system-wide risks, whose most relevant issue was the integrity of components supporting the drum during spinning. The 'slip' condition indicates when the machine starts sliding upon the floor, and the 'tip' condition indicates the situation in which the machine leans and tends to fall aside [30].

Function and organ models help relating system functions to system-wide parameters, to find out causes of the vibration problem. For instance, dampers under the drum (organ) help decrease (function) its displacement (body parameter) against the body of the washing machine. The dampers are assembled along metallic guideways to avoid excessive buckling. That condition would cause them to break, causing serious failure. Their properties, such as the elasticity modulus 'E', can be related to system-wide behaviour where the motion equation applies. Figure 3 shows system representations and the elements they support in reliability methods.

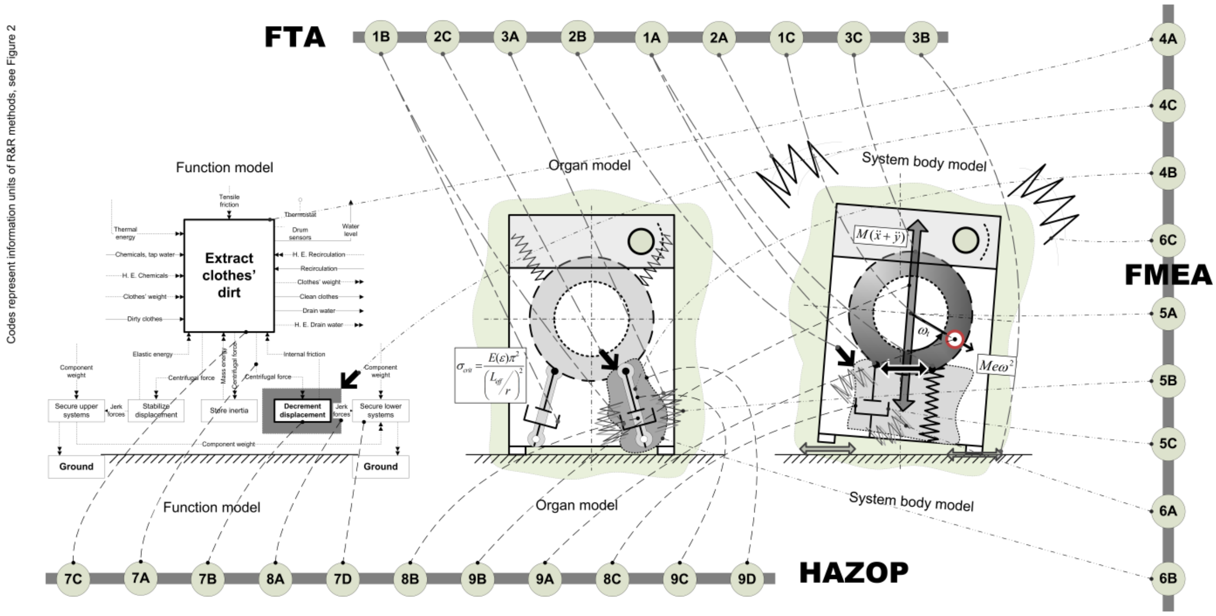


Figure 3 – Information units from R&R methods and its sources in system models (Figure 2).

The figure shows system models used in the study. While the function structure [13] is expressed as block diagram, the body sketch is used for the organ model [14]. The body model and its equations link to system parameter formulations [30]. The figure shows system representations, and respective components, feeding information to R&R methods and their information units, as in Figure 2.

The unit arrangement reveals R&R methods require variety of system descriptions to cover the system scope in increasing detail. Such requirement is neither uniform nor structured, which means all models are needed to carry out R&R analyses with these methods. The arrow directions hint R&R methods do not generally take advantage of early design models.

5.3 Taxonomy to R&R information in design

This item aims to propose a classification of the information required to carry out R&R assessments with DFR methods. It joins current knowledge from literature with insight acquired throughout the reverse engineering approach. A number of 273 keywords were collected from the dataset, and classified to main keywords from existing taxonomies and new keywords coming from data.

Current engineering taxonomies, providing main keywords to the R&R taxonomy, are referenced in the item 2.3. On current taxonomies, EDIT has lent most of the support to classifying design information with focus on R&R assessments. As shown in Table 1, all its information subunits – product, issue – have been retained. However, its original form does not lend sufficient support to describing design content related to assessing and improving R&R characteristics.

Subunits from current taxonomies with little or no relation to dataset keywords were discarded. New main keywords were synthesized on aggregating meanings of remaining dataset keywords, once there was no corresponding concept in current taxonomies. The set of main keywords used, shown in the Table 1, forms the R&R information taxonomy.

R&R keywords are described on the following characteristics: original reference, classification definition, subunit relations to original concept, and information source on models (Figure 3).

Table 1 – Main keywords for classifying engineering R&R information in design

Keyword	Reference	Definition	Processing	Source
Function	Functional basis [16]	Structured actions and system flows achieving a definite technical purpose	Retained original	Function model
Product	Engineering design (EDIT) [17]	Constructive elements, characteristics and relations from the designed product	Retained original	Organ model
Issue	Engineering design (EDIT) [17]	Relations, characteristics and requirements to be considered during product design	Retained original	Body model
Failure mode	Mechanical failure [18, 19]	Processes and phenomena causing degradation of performance or failure	Changed original	Body & organ
Event	Product dataset (Current research)	An occurrence where system properties and/or the functional state is changed	Created from data	Body model

Figure 4 shows an approximate correspondence between system models and R&R taxonomy keywords. They are followed by descriptions of specific system parts they apply to. For instance, component failure is illustrated by a buckling damper. Bold-contoured keywords have been either changed from original or created from data, whose subunits are shown.

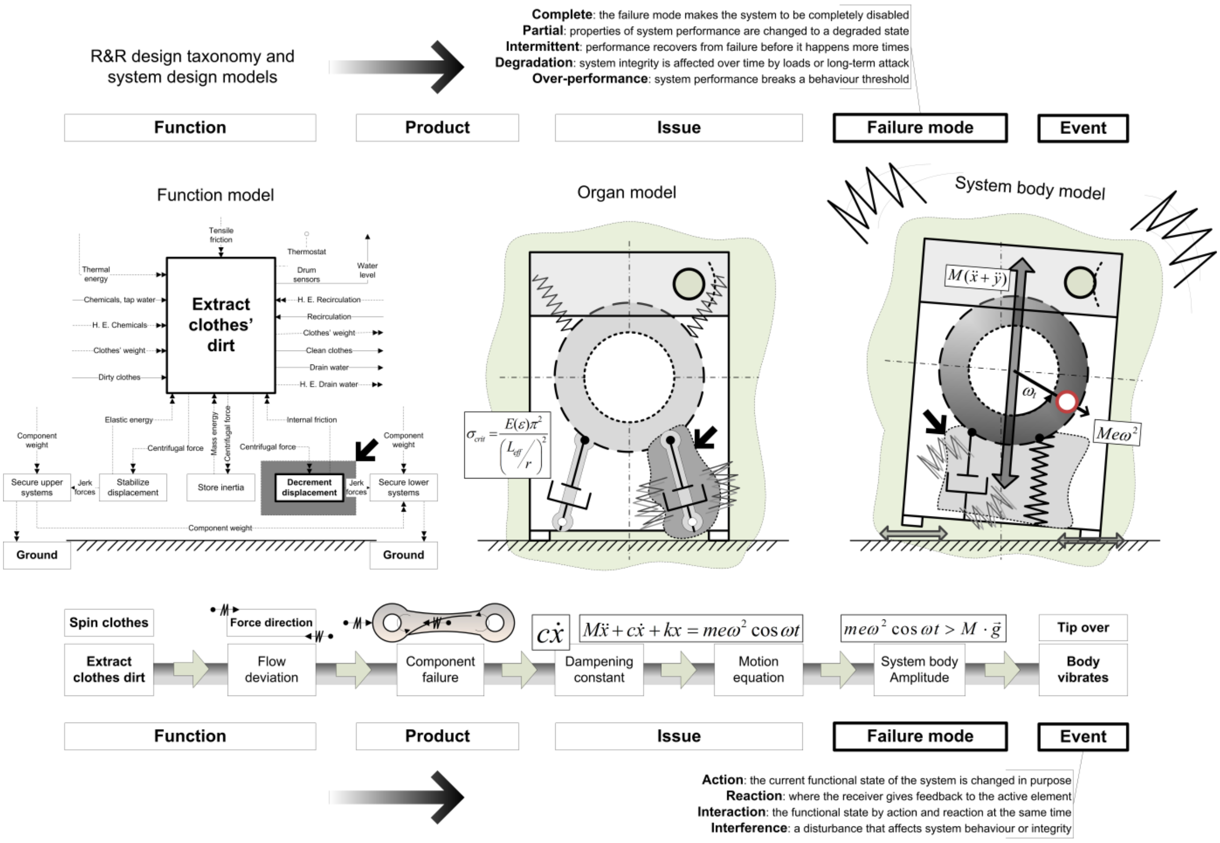


Figure 4 – R&R taxonomy: main keywords in correspondence to system design models.

Therefore, new keywords were developed in order to fill the gaps. Mechanical failure information is considered by a separate keyword because of its relevance in the research context. With redundancies found, a new classification on mechanical failure is proposed. The event concept is added as main keyword from the remaining information that did not fit to any of the other main keywords.

5.4 Tracing information demands from R&R methods to design models

This item aims to describe the information requirements of R&R methods throughout the analysis process. The assignment of metrics is made on the design information acquired from the system descriptions such as shown in Figure 3 and Figure 4. The squares in the table indicate the level of detail of product information, classified under the R&R taxonomy, which corresponds to information requirements from elements in R&R methods according to the information structures in Figure 2.

Design information is classified in detail, where system models on function, organ and body represent conceptual, embodiment and detailed design input, respectively. The subunits are positioned in rows and mapped to information units from R&R methods, assigned to columns. The mapping of information demands is shown in the Table 2 with letters indicating its availability on design stages.

Table 2 – Information requirements for the R&R assessment methods

Information availability
- ■ Concept design
- E Embodiment design
- d Detail design

R&R Taxonomy	R&R methods	FTA									FMEA									HAZOP										
		1. Gates			2. System_ev			3. Primary_ev			4. System			5. Failure			6. Analysis			7. D. Intent				8. Operability			9. Diagnostics			
		Gate OR	Gate AND	Gate INHIBIT	Top event	System event	Component event	External event	Conditional event	Basic event	Identification	Function	Component item	Operation mode	Failure mode	Failure effects	Failure detection	Severity class	Provisions	Flow element	Activity	Source	Destination	Guide word	Element	Deviation	Consequences	Action required	Causes	Safeguards
Function	Function	■	■	■	■	■	E	■	E	E	■	■	E	■	■	■	E	E	E	■	■	■	■	■	E	E	E	■	E	E
	Flow	■	E	E	■	■	E	E	E	d	■	■	E	■	E	E	E	d	d	■	■	E	E	E	E	d	d	E	E	d
Product	Component	■	E	E	■	E	E	E	■	E	■	■	E	■	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
	Interface	E	E	d	E	E	E	E	E	d	■	■	E	E	E	d	E	d	d	E	E	E	E	E	d	d	d	E	d	d
	Geometry	d	d	d	E	d	d	E	d	d	■	E	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
Issue	Environment	■	■	E	■	■	■	■	■	E	■	■	■	■	E	E	E	d	E	■	E	E	E	■	■	E	E	E	E	E
	Requirement	■	■	E	■	■	E	E	E	E	■	■	■	■	E	E	E	E	E	■	■	E	E	■	E	E	E	E	E	d
	Characteristic	E		d	E	E	d	E	d	d	■	E	E	E	d	d	d	d	d	E	E	d	d	E	E	d	d	d	d	d
Failure Mode	Complete	■	■	E	■	■	■	E	E	E	■	■	■	■	E	E	■	E	E	■	■	■	■	E	■	E	E	E	E	E
	Over-performance	■	E	d	■	E	E	E	E	E	■	E	E	E	E	E	E	E	d	■	■	■	■	E	E	E	E	E	E	d
	Intermittent	E	d	d	E	E	d	E	d	d	E	E	E	E	E	E	E		E	■	E	E	E	E	E	d	E	E	E	E
	Partial	E	E	d	E	E	E	E	E	d	E	■	E	E	d	d	E	d	d	■	E	E	E	E	E	d	d	E	d	d
	Degradation	E	E	E	■	d	d	d	d	d	E	E	d	d	d	d	d	d	d	■	E	E	E	E	d	d	d	E	d	d
Event	Action	■	■	■	■	■	■	■	E	■	■	■	■	■	E	E	E	E	E	■	■	■	■	■	■	E	E	d	E	E
	Disturbance	■	■	■	E	E	E	E	E	E	■	■	■	E	E	E	E	d	d	■	■	■	■	■	E	E	E	E	E	d
	Reaction	E	E	E	E	E	d	E	d	d	■	■	E	E	d	d	d	d	d	■	E	E	E	E	E	d	d	d	d	d
	Interaction	E	d	d	E	E	d	E	d	d	E	E	E	d	d	d	d	d	d	■	E	E	E	E	d	d	E	d	d	d

OBS: Numbers refer to information structure group divisions, as indicated in Figure 2

Black squares indicate the information is readily available with function models; grey squares indicate embodiment design information is required (represented by organ models); and, white squares indicate detailed design characteristics are needed to meet the information requirement of a given filed from R&R methods.

The information demands from FTA show the method requires functions to be considered system-wide, and then developed with progressive detail to link with component problems. Relevant requirements from FTA are:

- Top and intermediate events require action events and environment characteristics to be related with functions, which is feasible with early design models;
- Gates AND and INHIBIT require events to be understood as reactions and interactions, whose information is not readily usable with early design models; and,
- Basic events require product geometry and interaction events to be assigned and related to failure modes, information only available with detailed design representations.

FMEA requirements are primarily defined by the focus of the tool on system components. The FMEA analyses consider each component as an individual issue, which may manifest by different failure modes. Relevant FMEA characteristics are:

- System information in general and operation modes can be identified and set with function definitions and knowledge of complete failures, which is available in early models;
- Much about all other types of failure mode requires system models to provide at least information at the embodiment design level; and,
- Analysis fields such as provision, severity class and failure detection require degradation failure and product geometry to be described, requiring most design detail.

The results from HAZOP show emphasis in the link between function and flow parameters. HAZOP enables early identification of failure modes and events with early models, earlier than other methods HAZOP characteristics on this study are:

- Functions and flows bring significant input to describing the design intent and therefore to approach the operability problem;
- Design intent and operability fields are significantly accessible with intermediate design models, where mitigation requirements can also be established; and,
- While all fields require detailed information in product geometry and characteristics, deviations and safeguards are the most difficult to make clear;

6. Conclusions and future work

By carrying out a pilot case study with a reverse engineering approach, information requirements to R&R methods were assessed. R&R methods were decomposed in information units; graphic descriptions were organized onto system models; and, text descriptions into keyword data. System models and keywords were associated to existing taxonomies supporting R&R-specific classification.

Scoping information such as FTA system events, FMEA system description and HAZOP design intent are readily available with early design models. However, fundamental information such as FTA gates, FMEA effects, and HAZOP deviations is linked to product characteristics, and hence appears only in intermediate/detailed system models.

That means current methods can be initiated in early design stages, but cannot be concluded without significant effort in developing embodiment and detailed design information. The R&R taxonomy could support classifying available design information at early stages orienting new, specific R&R assessment techniques to concept designs.

7. Acknowledgments

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Information requirements of current methods for robustness, reliability and safety during early design phases

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Abstract

This paper addresses the application of methods for quality and reliability through the product development process, with focus on the use of methods for robustness, reliability and safety during early phases of the design process. This study aims to evaluate the information needed for the use of methods for robustness, reliability and safety (R2S), in order to assess the feasibility of their use during early design phases. For that purpose, reverse engineering was applied to a washing machine for acquiring information about the product design, representing it with models typically used in early design phases, and assessing their completeness of information for use with the methods. Types of information obtained about the product design and sources of information were categorized during the study, to generate a perspective on the information about product design that was carried by sources; then, models of the product were used together in order to generate input information for use with the methods for R2S in the study. The correspondence of input information to queries in the methods is visually evaluated in order to assess that can be fulfilled with the available information with models from early design phases. The execution of methods for R2S requires the following information about the product design being developed: intended functionality, working principle, architecture and behaviour in operation. These characteristics are only developed to structured representations of elements such as function structures and embodiment layouts, with incomplete knowledge of principle, component and use situation dependencies for use with current methods for R2S. Such information can only be obtained as result of knowing characteristics of product use, which then makes current methods for R2S only fully usable from detailed design onwards where prototypes can simulate events from the use phase in the product lifecycle. This points out to the need of new approaches to assess R2S attributes in support to design activities during early design phases.

Keywords

Robustness, reliability, safety, information needs, conceptual design

Introduction

Conceptual design is a critical phase of the design process where working principles and possible solutions are explored. During early design phases, the goals which a new product needs to satisfy are established, and the principles intended to solve these goals are developed. Such decisions have significant impacts on the quality that is delivered to stakeholders during product development (Mørup, 1993). The ability to assess how designs perform and how they can be improved can determine the feasibility of a project; yet there is a scarcity of information about how the design performs in early phases, as information is incomplete and may change over time, a fact which reflects the inherently uncertain character of early design phases. In this context, robustness, reliability and safety (R2S) imply perceptions of the extent to which the solution fulfils the expectations of customers and stakeholders; methods for R2S in product design also help manufacturing companies to strengthen their customers' trust in their products. The three concepts of robustness, reliability and safety are described as follows:

- Robustness reflects the ability of a system to perform its task with a minimum of sensitivity to variation that infringes on expected performance (Phadke & Dehnad, 1988). Methods that focus on the assessment and improvement of robustness aim to modify the characteristics of systems that are most sensitive to variations in their functionality. This can be achieved in two ways: firstly, by optimization methods that address functional parameters and optimize their selection to ranges wherein transfer functions are less critical (Phadke, 1989), thus minimizing dependencies between disturbances and functional parameters; and secondly, by synthesis guidelines (often referred to as design principles) that advise on how to deal with characteristics whose relationship to design parameters can be pointed out and recognized from experience (French, 1992).
- Reliability reflects the ability of a system to perform its task under specified conditions and for a given period of time (ISO 12100, 2010). Methods focusing reliability identify the characteristics of systems that deliver intended outputs while in operation, and assess impediments to their adequate functionality in use. There are two basic methods of analysing functions and scenarios with regard to reliability (ISO 31010, 2010) : first, eliciting expert knowledge about occurrences of failure due to characteristics of the system components and of their operation, against conditions that reduce the ability of components to function; and second, improving ability to predict the probability of particular scenarios, using knowledge about the history of similar products subjected to system-wide evaluation and assessment. Reliability methods work by enabling designers to assign priority to the weakest points, the elimination of which is critical if failure is to be avoided; by devising protective measures against the occurrence of failure; and implementing these in new product designs.
- Safety signifies a system's ability to perform free from unacceptable risk (ISO Guide 51, 2003). Methods that focus on risk assessment identify characteristics of systems that give rise to hazardous situations that may cause harm to people, property and the environment. These may be carried out in two steps: the first, identifies hazards that may occur during the operation of the system by using methods such as those used for reliability and also systematic what-ifs and checklists (Glossop, Ioannides, & Gould, 2005) for required components and procedures; the second involves seeking information on prior occurrences of incidents that establishes historical patterns of potential hazards, together with using risk matrices to provide quantitative/qualitative descriptions of severity from harmful incidents.

Process and function modelling approaches, which can be used to model products and processes, proceed by the reduction of system designs into logical units that perform partial transformations (Hubka, Andreasen, & Eder, 1988), to be solved by working principles and layout alternatives. Partial transformations are intended to simplify the generation of solutions that meet the criteria by expressing functions in terms of input-output flows. Combinations of system components in alternatives can be expressed in sketches (Buur & Andreasen, 1989), diagrams (Harlou, 2006) or virtual models (Baba & Nobeoka, 1998) that represent solution principles; their arrangement and the characteristics of their components assist in evaluating how design requirements can be met.

Knowledge about robustness, reliability and safety in the design process comprises complex information about product design, which must be conveyed in a way that simplifies its use. Design catalogues classify working principles in accordance with the type of transformation performed (locking, union, mechanism, joint), separating different working principles by their characteristics of complexity, kinematics and dynamics (Roth, 1994). Information involved in understanding how designs perform, such as failure modes and their mechanisms, is classified according to failure incidents as observed from experience (Bloch & Geitner, 1990; Collins, 1993). The design process as a whole contains implicit information on characteristics of the developing design, whose indexed information makes knowledge of the design more accessible (Ahmed, 2005).

Prior research has revealed that current methods for robustness, reliability and safety (R2S) may be started, but cannot be completed, during early design stages. This is due to the degree of detailed information demanded by the queries from methods R2S that were evaluated in the study (Marini, Restrepo, & Ahmed, 2010). Further work has ascertained that current practice in industry employs current R2S methods with a consolidate principle solution to conclude the detailed design activities; this is possible by the means of feedback from prior concepts that accumulates knowledge about the issues involved from experience with models and prototypes (Marini, Ahmed-Kristensen, & Restrepo, 2011).

These issues demonstrate the difficulties of using current methods of R2S, yet there is an interest in understanding how far they can be applied during early phases. Evaluations that recommend them for the purpose of safety assessments specify that they should be used in terms of phases of the design process (Pahl, Beitz, Feldhusen, & Grote, 2007); yet there is little understanding of the conditions governing their feasibility of use in early design. The present paper therefore aims to characterize how early design information can actually be used by current methods for R2S, in the interest of taking advantage of consolidate methods to address high uncertainty. This is intended as a contribution to the field of design methods, and aims to increase understanding of the use of current methods for R2S attributes in early phases. This is to be achieved in the following ways:

- First, by evaluating how information from early design phases can be applied to improve the execution of these phases; and,
- Second, by determining the degree of detail to which design issues can be assessed with current R2S methods using information from conceptual design.

The present paper is hence organized as follows: the Background section presents knowledge about R2S methods, their use in the design process, and the information supporting their use; the Method section describes our approach to collect and analyse the data; the Results section presents the outcomes of the empirical data analyses, which are discussed in comparison to current knowledge. Finally, the conclusions and implications are set in the Conclusion section.

Background

On the need to improve understanding of the feasibility of current methods for R2S during early design phases, we must reflect on the state of our current knowledge of these methods and on the context of their current use in the design process. For each of the design attributes presented in this section we must reflect on the following points: how current R2S methods contribute to quality attributes through the design process; the information that is processed by these methods; and at what stage in the design process these methods can be applied.

Methods for robustness aim to reduce the sensitivity of designed solutions to events that disrupt their functionality. Two approaches to robustness have already been introduced: dealing with the developing design in terms of parametric equations; and treating the developing design on its concrete characteristics from experience. Methods that tackle robustness problems on the basis of the optimization approach (Bras & Mistree, 1995) utilize the possibility of expressing design problems in mathematical relationships such as functions and correlations. They work in one of the following ways: either manipulating input values, or processing relationships within the design problem (Taguchi & Tsai, 1995). Their application is reported in individual cases, such as in the design of a thermal system for a solar energy plant (Chen, Allen, Tsui, & Mistree, 1996), or prescribed as part of a project-wide approach focusing on robustness, such as Six Sigma design (Yang & El-Haik, 2003) – successfully implemented in e.g. the telecom and automotive sectors. Robustness methods based on parameter optimization are recognized as difficult to apply in concept design; knowledge could then be obtained by recognizing links between component design and design parameters (Jugulum & Frey, 2007).

This entails a set of design rules that are formulated based upon the p-diagram, as much of the information regarding such relationships is not yet developed when product development projects are undergoing early design phases. The way this works is similar to methods for robustness problems that work by addressing characteristics of product design (Matthiassen, 1997). These synthesize knowledge accumulated from experience in design situations, for which guidelines are then suggested as ways of realising the desired performance. The process involves recognizing a design situation (e.g. component type and its loading), and recalling prior experience on how each situation is solved. This involves the identification of working principles and layout characteristics that can be changed, and justifying the positive impact of the proposed changes to design requirements (Smith & Clarkson, 2005). In the examples cited, existing designs from the medical industry and designs of construction machinery illustrate the positive influence of new designs towards the robustness of the system.

Current methods addressing functional characteristics of a system, such as FMEA and HAZOP (EN 60812, 2006; BS IEC 61882, 2001), embed part-of, from-to and cause-effect relationships in a product design through a sequence of fields arranged within spreadsheet formats. Their mode of application is to recognise wear and failure mechanisms resulting from intended and unintended operational use that is reasonably foreseeable. This is done by describing how incidents originate in individual components and how they may lead to undesired consequences. While these involve fundamentals that draw from current design expertise, these methods are mostly recommended for detailed design as they comprise thorough component-based assessments, where detailed component characteristics trigger mechanisms of failure.

Methods for reliability that are based on scenario assessment work by identifying scenarios where failures may occur, and by pointing out system components where defences may help avoid failure (EN 61025, 2007; Duijm, 2008). These methods use coherent descriptions of system structures that identify links between individual units; these are identified by means of intermediate devices such as gates or barriers that determine whether failure either escalates or is avoidable. Their mode of use evolves from a functional analysis in which all the system units involved in individual incidents are represented in their influence on the ultimate event, whether this be undesirable or even catastrophic. This is driven by the application of design expertise to the interpretation of system descriptions in order to construct scenarios for identifying critical components in the evolution of failures into undesired consequences.

Scenario analysis methods were first applied in the nuclear and aerospace industry, then their use has spread steadily to other reliability and safety-critical sectors such as medical and chemical industries (Kozine, Duijm, & Lauridsen, 2000). These are complementary to functional analysis methods, but they are less thorough regarding design components, as they aim to assess critical units with a view to avoiding failure escalation. The use of reliability methods for risk assessment reveals that reliability and safety issues are interdependent, in the sense that hazards must also be avoided just like failure and faults (ISO 12100, 2010). However, safety issues demand a stricter approach as they are concerned with more than just damage to property which can be solved by corrective maintenance: they concern namely damage to people, environment and society. Therefore, knowledge about safety is mostly contained in directives and standards that stipulate procedures for mitigating hazards during the design process of specific products such as machinery and medical devices (ISO 14971, 2008).

An alternative approach is to include such procedures in the design process by means of design-for-safety methodology (Wang, 1994) that aligns systematic design phases to risk assessment practice. This entails the use of current methods for safety and reliability along with statistical methods to assessing the probability and severity of incidents to be avoided. Knowledge about R2S attributes can also be extracted from information generated in the early phases, stored in product databases with schemas and representations of working principles; computer applications access databases of CAD models (Baba & Nobeoka, 1998) containing part and assembly information; and software with graph models representing the rationale of design characteristics (Wallace, Ahmed, & Bracewell, 2005). The degree of detail on which models characterize working principles and system layouts determines how available information meets requirements from current R2S methods, focusing on those based upon expert knowledge. Further information beyond the system layout was needed to satisfy the demand for information about issues derived from properties of joints and individual components (Marini, Restrepo, & Ahmed, 2010).

Methods for R2S are flexible in their application to different levels of detail in the design process (e.g. function, working principle, layout, embodiment and so on), in which the reasoning pattern is the same regardless of the resolution to which the design is characterized – for instance, more detail in sources will lead to a more detailed characterization of incidents. These methods also require considerable expertise from the designers who use them, as their use requires the recognition of design parameters and their behaviour that are implicit, using models and representations of working principles and design layouts. This paper seeks to understand how queries in current R2S methods can be satisfied with information typical from early design, by indicating how queries use information from sources characterizing R2S attributes of a product.

Method

Understanding which information formats are required when using current R2S methods during early design phases was considered an issue for research clarification within the methodology framework for engineering design (Blessing & Chakrabarti, 2007); action-research was deemed as the most suitable way of gaining hold on and insight into the issue. Figure 1 shows the stages in which the study was carried out: information was collected in the first stage from inspecting and reverse-engineering a product; raw data obtained from the inspection and disassembly of a manufactured product was converted during the second stage into typical models from early design phases; this information was then interpreted in the third stage into the format and queries of the R2S methods to assess the design issues affecting R2S attributes in the product.

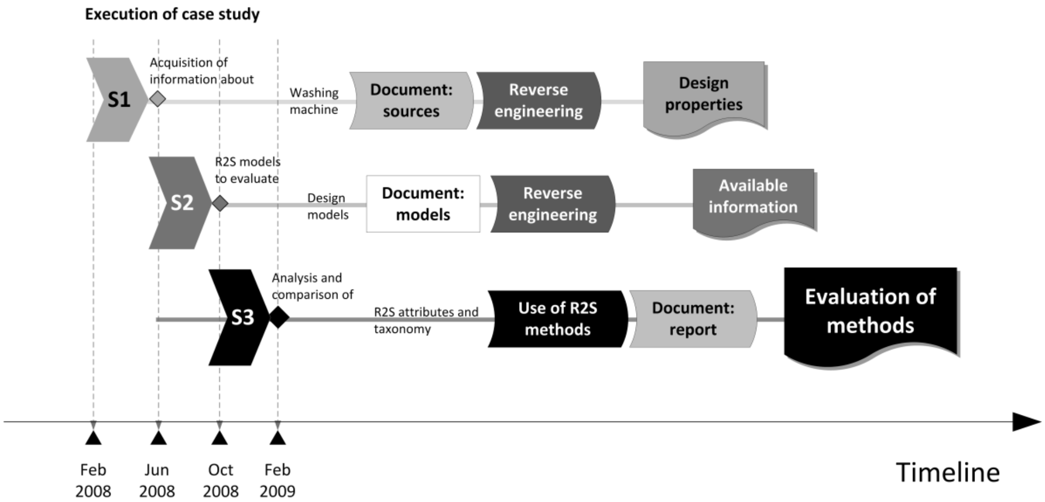


FIGURE 1 – EXECUTION OF CASE STUDY WITH METHODS TO ROBUSTNESS, RELIABILITY AND SAFETY

The approach to dealing with the data that was collected and generated was based on a case study approach (Yin, 1989) with document analyses as the main data collection method; the case study hereby reported was carried out as a pilot case on the purpose of building insight to determine an approach to support R2S attributes during early design phases. A manufactured washing machine was subject to a reverse-engineering approach (Otto & Wood, 1998); this was collected for use to assess R2S attributes within the format and procedures set by R2S methods used during the study.

To establish how the case study was to involve the use methods, theoretical sampling (Eisenhardt, 1989) was carried out prior to starting. The selection of R2S methods was based on the public knowledge of the acceptance and use of their protocols in industrial practice. Table 1 shows the characteristics of the case study performed for this research, regarding the selection of the methods for assessing R2S attributes and of the product for generating the design information as input to the use of the methods.

The methods that were selected for the study were performed according to the following prescriptions: FMEA: Failure Mode and Effects Analysis (MIL-STD 1629A, 1980); FTA: Fault Tree Analysis (Vesely, Goldberg, Roberts, & Haasl, 1981); and HAZOP: Hazard and Operability Studies (BS IEC 61882, 2001). The washing machine was selected as the product to be analysed due to its ubiquitous use, which assures the availability of information about how it works and about the design characteristics that give rise to issues with R2S attributes during product use.

TABLE 1 – THEORETICAL SAMPLING OF METHODS AND PRODUCT

Sampling	Main criteria	Approach	Outcome
Selection of methods	Relevance in literature Practical application in industry Insight provided on functionality issues	Web search of references Literature review on related topics Consultation with colleagues	Fault Tree Analysis (FTA) Failure Mode and Effects Analysis (FMEA) Hazard and Operability Studies (HAZOP)
Selection of product	Availability of public technical descriptions Product architecture with mechanical principles Availability readiness of product exemplar	Web search of references Consultation with colleagues	Washing machines Manufactured product and references about horizontal drum principle

The product was characterized in typical models and information formats from early design phases prescribed in systematic design (Hubka, Andreasen, & Eder, 1988; Pahl, Beitz, Feldhusen, & Grote, 2007), with the use of reverse-engineering (Otto & Wood, 1998) for the extraction of early design information and the analysis of conceptual design characteristics. This form of data collection enabled the acquisition of first-hand knowledge about the composition of the product, its functions and working principles; this was carried out through the process of understanding the components of the product into the intended information formats from systematic design methodology.

The main characteristic of the reverse engineering approach as prescribed by Otto and Wood approach is that it seeks to characterize the concept behind the product rather than early design information about it. This was a further reason for using this approach in this case study – namely, to examine the characteristics of the concept behind the washing machine, and how these are embodied in the product architecture. Once the outer panels were removed, an inspection enabled the identification of subsystems, their location in the construction and the links between them. In a second stage, part aggregates were inspected in their embodiments and interfaces to infer their working principles. These inspections were recorded by photography and written notes, subsequent to a 60-hour-long analysis between disassembling and inspecting part aggregates.

As some of the raw information obtained by reverse engineering was not supplying all the characteristics required, documentation about the use and maintenance of the washing machine was also acquired. Document analyses were carried out to analyse the data about the washing machine, focusing on specific characteristics that were seen as influencing R2S attributes in the product. For instance, the belt drive alignment between the motor and the drum was seen to influence the level of noise and the dynamic properties (reversing and acceleration) of drum rotation during the wash cycle.

To generate the results in this study, documentation was selected as it described links between R2S attributes and relevant properties of the washing machine. Pictures, diagrams and reports were chosen on their describing and matching properties of components in the washing machine as disassembled.

To simplify the output regarding types of information from the product that were involved in the assessment of R2S attributes with the selected R2S methods, coding was performed upon the dataset that was generated during the study. This approach involved drawing two classifications of information input for the use of the selected R2S methods:

- Firstly, information about R2S attributes from design characteristics of the product was classified into specific taxonomy identifying types of design information on R2S attributes as defined in Table 2; this was developed based upon knowledge in mechanical engineering about types of failure (Bloch & Geitner, 1990; Collins, 1993) and on engineering design research in government (Hirtz, Stone, McAdams, Szykman, & Wood, 2001) and industry (Ahmed, 2005) R&D environments, developing taxonomies for engineering design information. Deductive coding was performed and tested using 273 keywords extracted from working notes and the report. Categories from current taxonomies with little or no relation to the keywords in the data were discarded. The event type was defined from the keywords remaining, as there was no corresponding concept in current taxonomies.

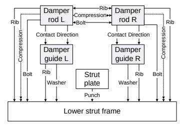
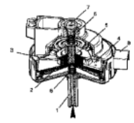
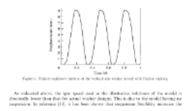
TABLE 2 – TYPES OF INFORMATION ABOUT R2S ATTRIBUTES IN PRODUCT DESIGN

Keyword	Reference	Definition	Source
Function	Functional basis [Hirtz et al., 2001]	Structured actions and system flows achieving a definite technical purpose	Function model
Product	Engineering design EDIT [Ahmed, 2005]	Constructive elements, characteristics and relations from the product	Organ model
Issue	Engineering design EDIT [Ahmed, 2005]	Relations, characteristics and requirements to be considered	Body model
Failure mode	Mechanical failure [Bloch & Geitner, 1990; Collins, 1993]	Processes and phenomena causing degradation of performance or failure	Body & organ
Event	Report from the case study – product data	An occurrence of change to system properties and/or the functional state	Body model

- Secondly, inductive coding in a similar approach to that used by (Busby, 1998) was performed to identify representation formats in information sources. Raw data included four reports containing detailed part renderings and 50 photographs from the product. Generated information comprised five flow diagrams, five body diagrams, and 20 sketches depicting design information on the washing machine, such as process, function and organ structures. Furthermore, 20 parameter identification tables and 150 tables on preliminary hazards were generated. Table 3 presents the code for representation formats, whose types were identified from concrete representations from documents in use or from models that were generated through the study.

The appropriateness of current methods for R2S in early phases depends on whether information about the concept of the product is available to fulfil the requirements defined by the structure and the queries the methods contain.

Table 3 – types of representation for the product

Types	Reference	Definition	Example
Photograph	Product photograph [Otto & Wood,1998]	Exposure of components in a product model to a camera that frames a determined field of view.	 Top view photo
Sketch	Representation of working principle [Hubka et al., 1988]	Embodiment representation of a product by freehand or software without fixed geometric scale.	 Process sketch
Diagram	Product architecture representation [Harlou, 2006]	Graphic representation of components and their interfaces without resemblance to product.	 Organ diagram
Drawing	Representation of part embodiment [Pahl et al., 2007]	Embodiment of parts of a product from instruments or software with fixed geometric scale	 Cutaway drawing
Report	Excerpt from test report [Conrad & Soedel, 1995]	Documented statement about static or dynamic attributes of parametric relationships.	 Graphic/text

To evaluate this, codes derived from literature were used as it contained accurate definitions of typical information formats in the systematic design process. This was used to make constructs that represent generic design characteristics, which is comparable to work in the ontology of generic activities in the engineering design process (Sim & Duffy, 2003): definitions from literature were applied to code generic design characteristics in information sources, characterizing the input to R2S methods across different design phases. This approach was used to distinguish aspects of design information for R2S methods that could be qualitatively measured.

We examined the codes in use on the following validities: construct validity, internal validity and external validity (Yin, 1989), described as follows.

- Construct validity refers to whether a code correlates with theoretical concepts: this was fulfilled through the use of information formats that represent the product concept, which are commonly prescribed in systematic design for early design phases.
- Interval validity reflects the characterization of cause-effect relationships within the scope of study; this was satisfied through linking information sources and queries in methods, through the use of codes about information identifying R2S attributes in the product, and about the documents that characterised properties of the product influencing its use.
- External validity considers the ability to generalize the conclusions that were obtained from the research procedure; this was satisfied by verifying this study against situations in other research about knowledge in engineering design – such as (Ahmed, 2005) – regarding the use of explicit knowledge followed by implicit knowledge from expertise.

Considering these degrees of validity, this research work is externally valid for practical situations where engineering knowledge is used to carry out methods for R2S in design processes, where mature products need to be rethought from the conceptual level in terms of their weaknesses; this study is also valid regarding the similar purpose of using R2S methods in this study in comparison to their practical use in industry. There, designers use R2S methods to find opportunities for provisions against risks of product use, through the implementation of new product functions or improved working principles.

Results

The information generated from the reverse engineering exercise represented the conceptual design of the washing machine, regarding its functions and working principles. This section presents the outcome of data analysis to identify the use of early design information and R2S attributes of the washing machine through understanding current R2S methods. The models were made explicit together with the information generated and with the correspondence between sources of information for R2S attributes of the washing machine. The reader may trace the use of information between sources and queries through the use of current R2S methods, and assess the levels of detail in the analysis that were made explicit and those that were taken implicitly.

TABLE 4 – SOURCES OF INFORMATION INPUTS TO R2S METHODS IN THE STUDY

Type of document	Acquisition	C/G	Design characteristics
Overview photos	Reverse engineering	C	Architecture, interfaces and embodiments in overall and close-up pictures
Close-up photos	Reverse engineering	C	Component embodiments, geometry of link features and assembly interfaces
Maintenance reports	Document analyses	C	Occurrence of malfunction, failure or damage linked to functions, parts and interfaces
Service manuals	Document analyses	C	Occurrence of malfunction, failure or damage due to failure or error during operation
Exploded perspective	Document analyses	C/G	Component links from frame to internal parts; assembly arrangement and part details
Free-body diagram	Document analyses	C/G	Working parameters of subsystems and their variables in governing equations
Experiment reports	Document analyses	C/G	Working parameters and their measurement units, with disturbances and their effects
System flow diagram	Modelling and representation	G	Main functional modules and flow of input into output, depicted with working principles
Function structure	Modelling and representation	G	System functions and flows through subsystem modules
Task structure	Modelling and representation	G	Sequence of tasks and operation modes depicted with process flows and control loops
Organ structure	Modelling and representation	G	Components and their geometries linked in architecture represented by flow diagram
Preliminary hazard tables	Modelling and representation	G	Working parameters of operating system module and their use conditions upon failure

Table 4 shows the individual sources of information inputs for the design of the washing machine, the procedure from which the information was sourced, and whether original sources were collected or were generated.

This indicates the use of available information in order to learn and evaluate design characteristics for the R2S methods selected for the study. The presence of generated documents indicates specific aspects from the sources acquired, which needed clarification through the reverse engineering approach. For instance, photos of the washing machine lacked clarity about the links between components in the product architecture: for that purpose, diagrams were used to represent the links between components. Design characteristics were extracted from collected sources into generated models, going backwards from product to concept through the reverse engineering approach, and then evaluated with regard to the relevant information types. The sequence of sources illustrates how information was acquired about design properties of the washing machine using the reverse engineering approach: sources were organized according to their level of detail about the design characteristics and R2S attributes of the washing machine.

Table 4 shows 7 sources collected as raw data and 8 sources which were generated: this indicates a trend to clarifying the raw information that was acquired with the reverse engineering method applied to the washing machine. The descriptions of sources illustrate the scope of design information used to obtain information for use with current R2S methods. Each source describes a defined range of characteristics of the washing machine, which involves a particular approach to extracting the information that is relevant for use with the current methods for R2S. For instance, geometric representations point out to component embodiments, link features and assembly interfaces. For the analysis, the availability of information for the R2S methods was assessed regarding types of representation in sources, which consist of product design descriptions that represent characteristics that are relevant for the identification of R2S attributes. Missing information for the methods could be partially compensated through the use of other available design representations, which were found as describing attributes similar to those needed.

TABLE 5 – SOURCES WITH TYPES OF REPRESENTATION AND TYPES OF INFORMATION ON PRODUCT DESIGN

	Conceptual design	Embodiment design	Detailed design
Photograph	**N/A**	**Product**: *- Overview photos*	**Product**: *- Close-up photos*
Sketch	**Function:** *- System flow illustration*	**Product:** *- Exploded perspective*	**N/A**
Drawing	**N/C**	**Product**: *- Exploded perspectives*	**(N/C)**
Diagram	**Function**: *- Function structure* *- Task structure*	**Issue**: *- Free-body diagram*	**Product**: *- Organ structure*
Report	**Issue**: *- Preliminary hazard tables*	**Issue**: *- Experiment reports* **Failure mode**: *- Maintenance reports*	**Event**: *- Maintenance reports* **Failure mode**: *- Experiment reports* *- Service manuals*

This can be observed by the information predominant for each type of representation found in sources, whose characterization of the product has less detail and accuracy than usual models that were missing. To this end, Table 5 gives an overview of how types of information are carried by sources across different types of design representation, and through phases of the design process. Documents and individual representations from the acquired data were analyzed with a view to their use for the R2S methods. The types of information from the documentation and the instances from which these were examined determined to which detail the identification of R2S attributes was possible at the concept design phase. As shown in the table below, a system flow illustration was generated through a sketch depicting how the system is formulated in functions. However, further sources were needed to relate representations of working principles to their operation in use, such as links between iconic illustrations of components and elements of the task structure regarding the intended use of the washing machine.

Such example demonstrates the partial compensation for unavailable information within the sources of information for R2S methods. The drawback of having different sources of information can be compensated for by providing overview representations of design problems. For instance, photographs determined the scope of viewable embodiment of components from the washing machine, in addition to which complementary information with notes was needed to identify embodiments that were not visible from the views in the photographs. The representation of the washing machine with sketches and diagrams was often simplified: sketches often omitted information about design details for the sake of clarity; this was rectified by diagrams stating all relevant elements in the architecture of the washing machine. Reports constituted the single most relevant information source with regard to R2S – due to the fact that they combined a number of design representations.

For the R2S methods reviewed, information regarding product functions was needed. These involved the declaration of the system functions and flows in energy, material and information. Such representations state the entities that are transformed through the system, and the transformations through which the system processes its intended outputs. Yet the entities being transformed – flows of energy, material, information – have properties which constitute design parameters. In addition the need for information about function, content about issues was relevant for the R2S methods reviewed. Issues involved the definition of requirements to working principles, related to their functional performance and their behaviour through the lifecycle – prescribed in should-be basis. Individual parameters extracted from properties of functional flows, along with implicit knowledge of their intended working ranges, constitute input to processing R2S attributes in such design issues. For instance, characteristics such as the material and the surface roughness in the internal water ducts of the washing machine determine whether these ducts will be more prone to limescaling; this impairs quality and efficiency of the water flow in the ducts.

Information about failure modes was missing from the characterization of working principles in the washing machine; as a consequence, product characteristics are only useful for R2S methods once embodiment design characteristics have been defined. This includes the arrangement of components in the system and the design of their geometries, as well as the definition and characterization of the interfaces that define the desired degrees of freedom among components. In this regard, exploded perspectives represented information about the product architecture and the embodiment of its components. This aids in extracting issues from component descriptions in terms of shape and interfaces, along with the primary failure modes.

Complete information about failure modes and consequent events is only generated by the detailed design information, which is provided by sources such as provided by photos, organ structures and service manuals. If there is no prior detailed information that can be drawn upon, such characteristics need to be defined for a complete understanding of how the product works to be achieved.

An example of how seemingly different representations correspond and complement each other is shown in Figure 2. The figure presents design representations used for the identification of preliminary hazards, information that refers to the concept of the washing machine. The representations shown consist of: a function model emphasizing a single function – stabilize displacement; a system flow illustration aggregating working principles for all functions of the machine where the carriers of the highlighted function are indicated; a mass-spring model representing the physical mechanism in the working principle, where the spring component is highlighted; a parameter identification table stating physical parameters through the highlighted function; and a preliminary hazard identification table for the spring constant parameter that characterizes the highlighted component in the mass-spring model. The dashed lines with arrows show how information about R2S cascades from earlier concept representations to analyses of how components in the concept are intended to perform during use. Links also represent relevant types of information implicitly considered in the formation of input to R2S methods.

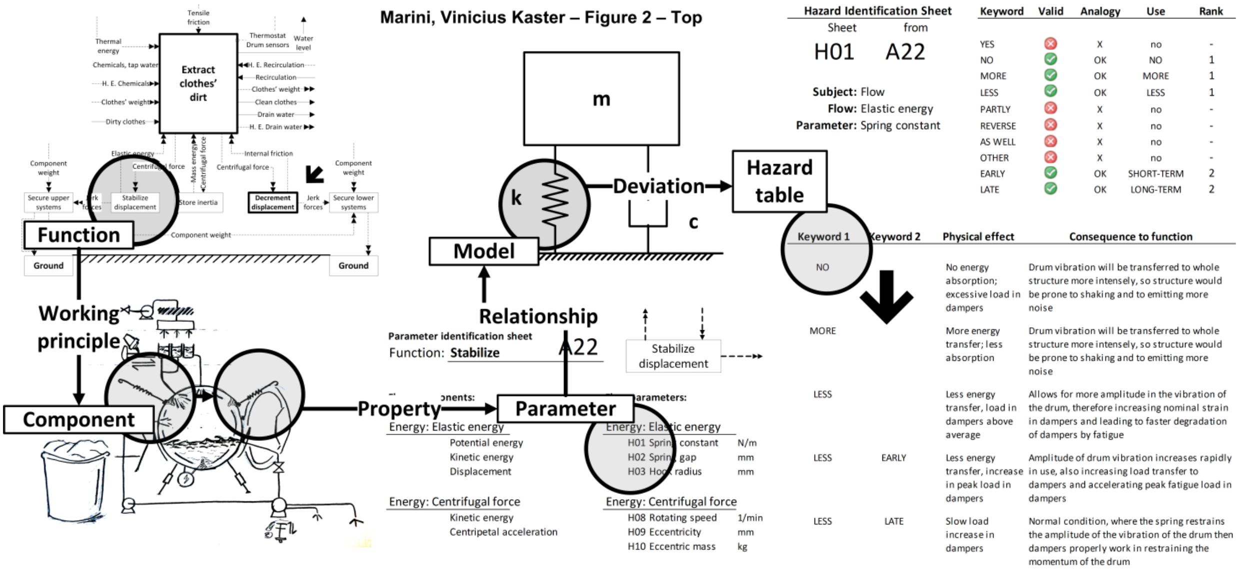


FIGURE 2 – CORRESPONDENCE OF INFORMATION ABOUT R2S BETWEEN DESIGN REPRESENTATIONS

The figure includes models representing the following information:

- Function defining the transformation – the stabilize displacement function is intended to transform centrifugal force into elastic energy, thereby filtering jerk forces transmitted to the structure of the machine;
- Working principle implementing the transformation – the hanging springs work by absorbing an amount of centrifugal force from the mass eccentricity of the spinning drum through their displacement;

- Components and embodiments performing the transformation – hanging tension springs are intended to absorb centrifugal forces generated by the mass eccentricity in the drum during the operation of the washing machine;
- Parameters associated with the transformation – accumulated energy by the spring is intended to stabilize the displacement of the drum within the structure frame is expressed by a physical parameter: the spring constant; and,
- Preliminary hazard table for the spring constant parameter – by affecting the performance of the spring to accumulate energy, variations in the spring constant affect the displacement of the drum with changes in behaviour of the washing machine.

Earlier representations such as function and task models delineate the path for the navigation through the characteristics of the system. This is essential for the use of R2S methods, as they require proper system definitions in order to clarify how R2S attributes are at risk either by characteristics of the design of the product (function) or by its operation (task). Their interpretation permits generating information about the characteristics of the system that directly influence R2S attributes. This orients the approach of analysis on working principles, which were physically characterized in the following ways:

- The way the working principle is held together in the structure – location, interfaces and neighbour components - is described in the embodiment of the product architecture;
- The parameters of components and behaviour that are involved in the implementation of the intended function are physically characterized in free-body diagrams and equations.

This is done from the system flow representation to the parameter identification table, which was generated from characteristics of the working principle, shown in the right of Figure 2 as result from linking across the other sources.

Models such as those shown in the figure were used to represent the concept of the washing machine in a prescriptive manner. Function models make explicit the intended transformations for the product and the entities that are flowing through them, and models of working principles represent characteristics of the product embodiment and behaviour parameters involved in the actions for implementing the product functions. The information made explicit in these models does not directly support the evaluation of R2S attributes, as characteristics of system layout and its performance are largely absent. As a result from performing the study, models typical from early design phases were seen to direct the search for further information on the intended performance of the product; this means that such models indicate the relevant knowledge needed about the functionality of the product concept.

In order to evaluate how attributes of R2S could be generated or affected by product design, it is also necessary to use implicit knowledge – and this is produced by interpreting the available models in the light of further knowledge derived from experience of similar products, or from the measurement of performance with available prototypes. Within our reverse engineering approach, such information was derived from experience with operating similar products, which revealed the influence of parameters such as the weight of clothing on the functions displayed in Figure 2. Information about a manufactured washing machine was recorded photographically in order to document characteristics of components and their interfaces in the product, linking between product concept information and resulting behaviour from the implementation of working principles in the product architecture.

The Fault Tree Analysis (FTA) in Figure 3 gives an example of information that is provided by current R2S methods. Top events in FTA regard system-wide failure, which can then be reduced to partial faults upon which occurrence of the ultimate event is conditional. The fault tree was designed around the overall dynamic behaviour of the washing machine, with partial faults being defined as intermediate events in the side branches. Characterization of fault causation at the bottom of the fault tree necessitates information about the integrity of system components. This illustrates the difficulty of using information from early phases and the lack of knowledge regarding body and material properties of components in the system. The layout of the fault tree presupposes an understanding of the effects of variations in functional parameters over system-wide behaviour. The fault tree shows degrees of magnitude of overall vibration from faults involving the transfer of force from centrifugal force to the structure of the machine and then to the supporting floor – the circle on the body diagram in the upper left of Figure 3.

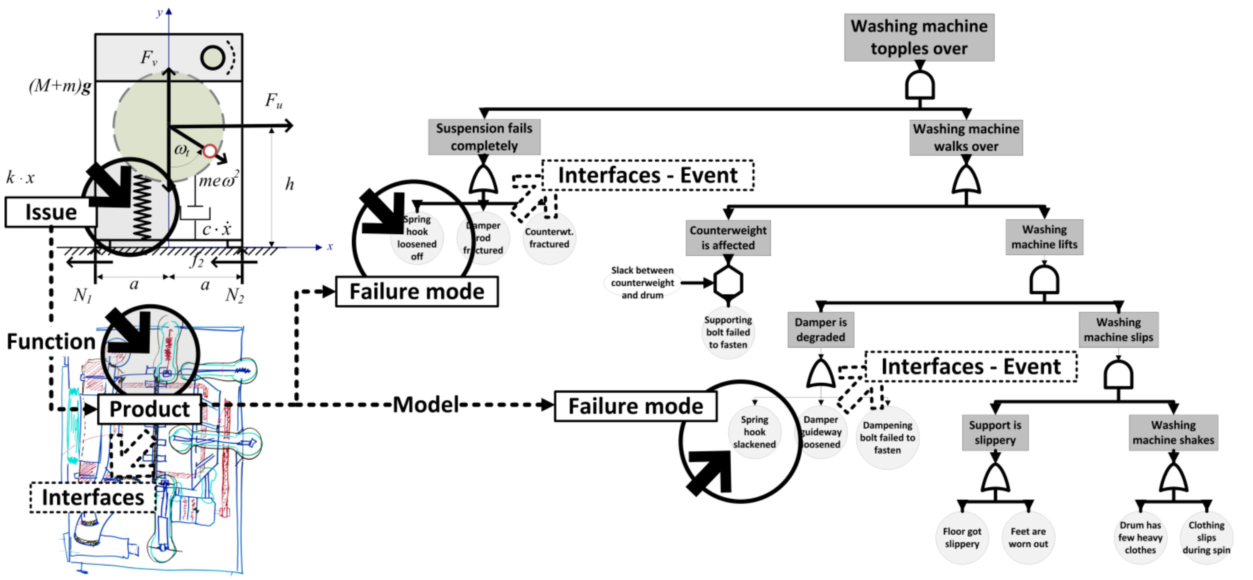


FIGURE 3 – FROM SOURCES OF INFORMATION TO QUERIES IN METHODS – FAULT TREE ANALYSIS EXAMPLE

In the fault tree, these degrees of magnitude are associated with progressive intermediate events whose behaviour is increasingly severe. Faults in system components causing the escalation of system behaviour originate in component states and in component links in the product architecture - the body sketch at the lower left of Figure 3. Component links determine the nature of the gates in the fault tree and the location of branched intermediate events throughout the fault tree (the broken red line from body sketch in the lower left). The representations convey relevant information about components influencing R2S attributes, and about their arrangement in the architecture of the system. The events depicted in the fault tree represent states of functionality in the spring component that derive from the estimation of changes in the spring constant beyond intended ranges, and their effects on system-wide events through interfacing components. Early design information was used to carry out early analyses with current R2S methods, considering that physical parameters were known to characterize the working principle that implements the intended functionality.

This is demonstrated by physical modelling of the spring-damper suspension system in the concept of the horizontal washing machine, complemented by links between physical parameters and preliminary dimensions in the working principle (Conrad & Soedel, 1995). This is reflected in the link between the spring constant and characteristics of the spring principle, such as whether it is a tension or compression spring, as well as in its location in the system layout. These links allow a preliminary estimation of behaviour beyond the working ranges, which is the kind of information actually needed to fulfil the conditions for satisfying the event definition as a query within the FTA example.

Discussion

The study of the use of early design information for current R2S methods reveals that the information used must characterize the product concept, regardless of whether it is a new variant design or an original design. To identify characteristics of product design with influence upon R2S attributes, a minimal scope of information must be fulfilled. This is, first and foremost, the role of early design methods: to describe what must be known about the product regarding its concept and intended application. The acquisition and development of such information as performed in this study has its primary focus on information about R2S attributes of motion damping, which processed over the centrifugal force from the drum to the structure of the washing machine. Typical model in early design phases – as shown on the left of Figure 4 – the function model describes how the system is decomposed to satisfy the purpose of washing clothes. It indicates the elements that each unit transforms in order to deliver the clothes at the end of the washing cycle.

Knowledge of these elements indicates the physical properties that need to be transformed by working principles, whose combination is represented in the organ model. Intended transformations between states of physical properties that are carried by working principles serve as criteria for establishing intended performance and identifying issues arising from the non-attainment of intended working states. Such information was mostly obtained from interaction with the washing machine and from knowledge of the use and maintenance of the product.

Such development is shown from the left to the centre of Figure 4, where information becomes increasingly unclear and uncertain. This approach is parallel to that which uses meta-behaviour models in support of FMEA analyses (Kmenta & Ishii, 1998) , where behaviour-structure relations are made explicit and then decomposed in order to identify intended working states and assess possible failure modes which deviate from these. As the product used a case of adaptive design, it becomes clear that information obtained from product use is used to identify intended operating states and systematically to assess events that trigger deviations from these. This means that qualitative information generated in early design phases does support the execution of current R2S methods to the level at which working principles and system layout representations indicate probable issues within the reach of prior knowledge. As we chose to study the washing machine, the available information on its use and maintenance helped to clarify the events that were relevant to R2S attributes in the product.

Through the use of prior knowledge together with information from the product lifecycle, this approach helped to generate FTA analyses for to basic events in components from representations of working principles of the washing machine. Qualitative descriptions of failure utilise information from current products to make examples of information models about reliability (Derelöv, 2008) for database models that characterize failure modes in components linked to working principles.

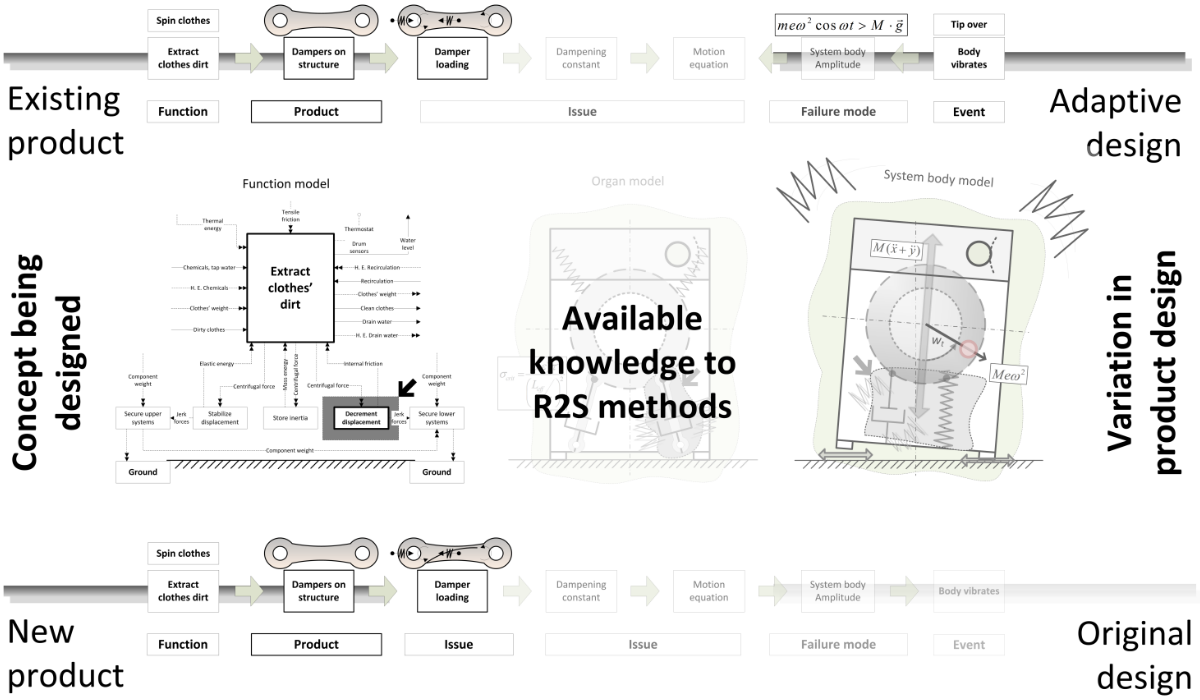


FIGURE 4 – ON THE APPLICATION OF METHODS TO R2S DURING EARLY DESIGN – SCENARIOS OF USE

As the approach used by Derelöv identified working principles from produced products, it was found to employ a method for extracting information about R2S that is similar to this study. Models such as these address the qualitative aspect of factors which influence R2S attributes that need to be considered before a new product enters the market. However, experience with current R2S such as this study and from other cases such as with R&D of mechanical systems (Marini, Ahmed-Kristensen, & Restrepo, 2011) shows that working ranges and variation issues cannot be easily assessed with information available from early design phases.

While the use of available information from early design phases allowed the clarification of design issues though the study, the incompleteness of information about parametric relationships within early design models prevented more accurate assessments about quantitative attributes of R2S such as frequency and severity.

Conclusion

This paper examined the use of information during early design phases to characterise information about attributes of robustness, reliability and safety (R2S). Through the use a reverse-engineering approach, sources of information about the product concept of a washing machine were used in order to conclude queries in current R2S methods. Product information was thus aggregated in models and representations to either delineate the product concept or to clarify issues arising from early design models. Correspondence between units of information from early design stages showed progressive understanding of information about R2S characterizing the performance of the washing machine, where early models elicited knowledge about the functionality of subsystems and components in the washing machine. Engineering knowledge was elicited through this mechanism, which involved analogies between the information available in the models and that obtained on the lifecycle of other products. Further information was then generated to represent and explore the working principles of the washing machine, indicating operational states and functional parameters linked to embodiment characteristics.

Early design models manifest a prescriptive approach to how the product works, but they can also be interpreted to yield issues concerning whether the product will perform as intended. The information available during the study aided the clarification of intended system functionality, qualitative characteristics of working principles and their embodiments, and primary parametric relationships explaining the succession of influences to R2S attributes. However, use information was needed as input to characterize operational states of the product and their working ranges regarding performance parameters. Besides, more precise parametric relationships describing functional and architecture dependencies were not available during the study. This enabled us to characterize faults in the system and their escalation to system-wide effects, yet it did not provide the quantitative information necessary to assess the level or the extent of risk deriving from failure in product design. Hence, the information that is available during early stages for the assessment of R2S attributes of a product was not sufficient to complete the execution of the selected R2S methods: FMEA, FTA and HAZOP.

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INFLUENCE OF DESIGN EVALUATIONS ON DECISION-MAKING AND FEEDBACK DURING CONCEPT DEVELOPMENT

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ABSTRACT

This paper aims to understand the following issues: how design flaws motivate the rejection of alternatives, and how they influence design feedback. A longitudinal, descriptive case study was carried out following the generation, evaluation and selection of design alternatives generated over two and a half years, with the following results: the lack of R3 evaluations during early design stages is confirmed; causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles; and, design feedback lacks clarity in early stages, stated in a generic manner when present. Recommendations are given to capture designers' preferences and insight to address robustness and reliability in early stages, and to use this knowledge in order to support these attributes by prodding designers to propose countermeasures.

Keywords: Concept development, design evaluation, decision-making, design feedback

1. INTRODUCTION

Key design characteristics are established during early design stages, which determine the fitness and dependability of the intended solution to the market. These phases offer more room to decision-making [1], and development activities in these stages lead to more effective solutions that enhance the competitiveness of the manufacturing organization. Among other objectives, robustness and reliability stand out as critical goals companies need to achieve. As consequence, keeping good reputation will make customers to prefer their products. If approaches and methods to assessing reliability, robustness and safety (R3) issues require significant amount of data and expertise [2], there is need to know how designers address the challenge. This paper aims to evolve the issue of R3 considerations in early design stages by studying how they are assessed in an actual project. Following concept development activities in industry, a two-and-a-half-year longitudinal case study incorporates the role of the industry context in shaping how R3 issues are addressed in early design stages.

2. BACKGROUND

Models, methods and practice in conceptual design

Models: they are used for several purposes, from visualizing solution configurations up to prescribing how solutions should work [3]. Functional modelling decomposes an overall function into chains of energy, material and information flows [4]. Organ modelling can describe components and their links by sketches [5] or flow-charts [6]. Together with these methods, taxonomies aim to separate and structure design issues in manageable sets. Mechanical connections [4], design information [7], and robustness strategies [8] constitute examples supporting the elicitation of design issues.

Methods: they embed design knowledge in form of principles that constitute basis for opportunistic design [9]. The argument of design principles has been developed with focus on robustness and reliability for mechanism design, comprising guidelines for use at the conceptual, embodiment and detailed design stages [10]. Methods can also prompt designers to think systematically about problems, and offer opportunities to spot and communicate design flaws. Some have become widely used in industry with international standards available [11, 12, 13]. Others have their use restricted to designing, operating and maintaining large-scale systems with inherent technical risk [14, 15].

Practice: it may provide a generic overview on the design process [4] or can emphasize different views on the engineering design activity: managing as a nesting, multi-faceted set of activities [17]; and providing guidance on methodologies dealing with variation [16]. Such references evaluate options for design practice against technical risks, and assess its suitability to design cases and phases by the means of expert opinion [16]. Risk management is also a concern as a supporting process towards the best possible outcome from design [2].

Development management on conceptual design

Integrated multi-disciplinary development: Along with product development management, product design considerations had to change in order to accommodate new competitive needs. Multiple-technology and multi-domain designs, and the need for their fast integration, have given birth to product architecture considerations [18]. Modularity has particular importance, because it influences development management, design flexibility and product performance [19]. Also, overarching approaches to quality and robustness were developed to reconcile needs of management with design performance requirements [20, 16]. This body of knowledge shows the design process as a multi-faceted activity, with many parallel and nesting sub-processes underway [17].

Continuous learning and experimentation: the choice of simulation or prototyping for experimentation is influenced by factors such as simulation realism, cost of prototype-building, and information to correcting errors. Expensive prototype-building, risk-sensitive designs and complex error correction processes influence the need for increased simulation and increased headcount to screen design errors and reject bad designs [21]. More expensive test procedures and difficulties in fitting test conditions to design requirements will make parallel testing less attractive. Integrated, tight-packed architectures are more likely to require sequential and iterative testing that increases and improves learning. However, parallel testing on different alternatives will provide more options to choose the best design [22].

Concurrent and continuous engineering feedback: problem-solving cycles were made overlapping by early information exchange between engineers and smaller innovation leaps [23]; design lifecycle stakeholders were included in development tasks in multidisciplinary team management strategies in contrast to their absence in traditional practices [24]. Set-based development follows three basic principles: design feedback is anticipated and carried out as a continuous process since early design stages; designs for different subsystems and development stages are continuously fine-tuned and fit to each other up to a late design freeze; and, the development process includes continuous verification of mutual and conflicting constraints for adjustment [25].

Decision-making and feedback practice

Decision-making depends fundamentally on the set of values carrying the preferences of those involved in making the decision [26]. An experiment on decision-making has assessed the influence of time, methods and behaviour, obtaining the following respective results: relative importance of criteria was assigned short time; formal methods did not influence to the explicit justification of evaluation; and behaviour has not involved the production of thorough documentation [27].

Feedback is seen as neglected in design organizations, because of four main problems: neglecting previous outcomes; design-related errors are repeated; unreliability of feedback from outside; and the mostly negative nature of feedback received by engineers. [28]. Nevertheless, it is significant for learning from failure in design and preventing it by innovation. Besides that: successful correction of design flaws depends on the involvement of designers, and on evidence from warranty claims and/or testing; mechatronic (integration) problems are more often successfully corrected; and, flawed original designs are more often corrected successfully than adaptive ones. Effective cross-project communication and knowledge management should guide designers towards better solutions [29, 30].

3. RESEARCH METHOD

This work consists of an investigation about improving the ability to manage technical risks during early design phases. R3 methods would not be completed this scope because the information they need needs to be drawn from detailed design models [31]. In response to that, our aim is to investigate the following processes in industry: how design flaws motivate the rejection of alternatives, and how they influence design feedback. That will help to find ways to improve the management of technical risks by focusing R3 attributes in early stages.

This study deals with a mechatronic, precision-mechanics medical device. It is a performance-critical system, especially on R3 issues, due to life-threatening implications from failure and performance fluctuations on blood sugar concentration. The case study approach [32] involved analyzing concept design information generated over two and a half years within a product development project of an insulin injection pen, as shown in Figure 1. Timelines are shown in four layers: the product development timeline at the company, the product development stages [33], the stages of executing the case study, and, the timeline of collecting data from documentation and interviews. The study was started by March 2009 and finished by April 2010, with a timeline of information from December 2005 to March 2009. Deliverables to this paper are represented by R1 (concept development), R2 (rev. engineering plus design decisions) and R3 (rev. engineering plus technical risk management).

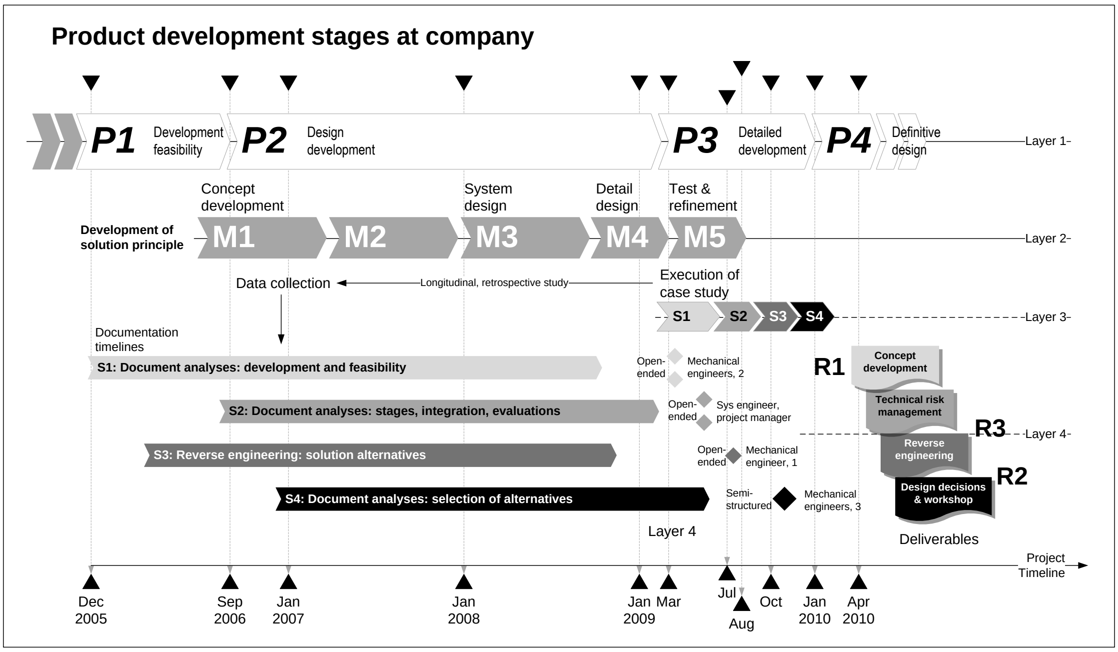

Figure 1 – Timeline of industrial case study

The execution of the case study is characterized in five elements as shown in Table 1. General characteristics of the case describe the involvement of the researcher and the conditions of study; document analyses describe evidences collected from project documentation with relevant information; reverse engineering describes characteristics of design alternatives that were relevant for the findings, interviews describe the approach used, the participants and their roles in the project, and the use of mediation and media to record information; modelling and representation describes relevant characteristics of findings represented in this paper. Document analyses, reverse engineering, and modelling and representation are also situated in relationship to interviews.

Table 1 – Research approach for industrial case study

Characteristics	Doc. analyses	Rev. engineering	Interviews	Modelling/represent
Case executed with actual project	17 partial/closure stage presentations	4 sketch sessions of work principles	5x open-ended on R3 development issues	9 function modules in all alternatives
Researcher observes project	5 technical risk stage reviews	20 alternatives of solution (concepts)	3 mechanical engineers, 1 system engineer and project manager	Several overview and close-up screenshots of alternatives
Longitudinal and retrospective study	14 feasibility reports on features	50 CAD variants with small changes	Not mediated, with video records. (45min each)	3 sequential/timeline development graphs
Comprehensive study of situation	4 matrices about set-based dev.	9 modules in system formulation	3x semi-structured on concept selection decisions	Total of 50 failure occurrences to reject
36 months from sketch to solution	Several reports from evaluations	61 work principles in all alternatives	Mechanical engineers: 2 veteran, 1 expert; Risk specialist	Total of 47 mentions to technical risks
Lead time launch in 6 to 8 years	Validated by interviews	Associated to interviews	Specialist as mediator, with video records (60 min each)	Developed upon interviews

The work has been carried out in a retrospective and longitudinal approach to the design process, fitting into a descriptive study approach [34]. Document analyses were carried out through the whole case, to understand when concepts were generated, which models were developed, which issues took place and when concepts were discarded. Reverse engineering [35] was used to identify the functions performed by design alternatives, their working principles [36, 37] and similarity between these. The project team was composed by the project manager, three mechanical designers (two veterans), one risk specialist, and three electronics engineers (one veteran). Open-ended interviews were carried out with all mechanical designers, one system engineer and the project manager. Semi-structured interviews were carried out with mechanical designers only. Questions asked to interviewees focused two types of issues: challenges and measures to manage technical risk (open-ended), and the rationale for selecting and rejecting design alternatives (semi-structured), to guide the search for information and validate the findings from documentation and reverse engineering, respectively

4. RESULTS

The study was carried out with support of system-related methodologies to undertake analysis and evaluation at a system level with the following considerations on concept development:

R1: Concept development timeline: this item represents the concept development process as found in industry, in the following aspects: the use of design models, their levels of detail and concreteness; the following milestones represent the development of alternatives: start, stand-by, reject, pass to detailed, reject detailed and change to solution principle; dashed lines identify occasions when R3 methods are used: to evaluate and select; to refine and select; and, to asses risk.

R2: Influence of procedure on failure modes: this item shows failure modes that motivated the rejection of design alternatives. These are identified as: primary failure modes explicit in documentation; and secondary failure modes found by validating rev. engineering with interviews; failure modes repeated due to reusing working principles from earlier alternatives that were rejected are identified with dashed hooks linking earlier and later occurrences.

R3: Technical risk feedback from failure modes: this item describes design feedback issues mentioned by designers, which denote design attributes that need to be improved in further alternatives. Issues are tracked down on when they appear and how their ranking changes throughout the stages of concept development. They are also characterized on whether they become most critical or least critical considering design attributes analyzed in design alternatives.

R1: Concept development timeline and methods

In early stages, only two alternatives were put on hold during development, all others to AS3 being rejected. Comparison matrices of alternatives (Cn) were the method of choice for early stages (milestones 1 to 4) along with others: a safety-focused product benchmarking (P1); feasibility analyses (Fn) up to milestone 3; and an assessment of the influence of working principles to sensors (T1). The last set-based comparison (S4) was performed along with a tolerance-based evaluation of alternatives (E1) and a Pugh matrix supported by comprehensive discussion (R1). As result, 4 further alternatives were generated and passed to proceed with system design. Later milestones were carried out to evaluate and refine the remaining alternatives. Milestones 5 and 6 involved conceptual DFMAs (Dn) to evaluate integration and production issues, and a further performance evaluation (E2). In milestones 7 and 8, math-based and FEA simulations (Q1, Q2) were performed along preliminary hazard analyses and introductory HAZOP (H1, H2). Only two system design alternatives were further developed to detailed design, so that a single solution principle was generated. Milestone 9 involved team-based evaluations with standard R3 methods: a linked HAZOP + FTA (H3) and a thorough FMECA (H4).

Figure 2 shows the concept development timeline. The developed alternatives are shown in the vertical axis, with the design stages shown in the horizontal axis along with available models throughout concept development. The legend in the figure indicates the development states of alternatives and the milestones of alternatives being rejected, put on hold and passed. Evaluation milestones, indicated by filled triangles along models providing design data, show when R3 methods, indicated in hollow inverted triangles, were performed during the project. As result, 8 evaluations are performed on 14 alternatives, while the other 6 are evaluated with 12 instances. That shows the lack of R3 evaluations during early design stages, a problem this paper aims to explore with further detail.

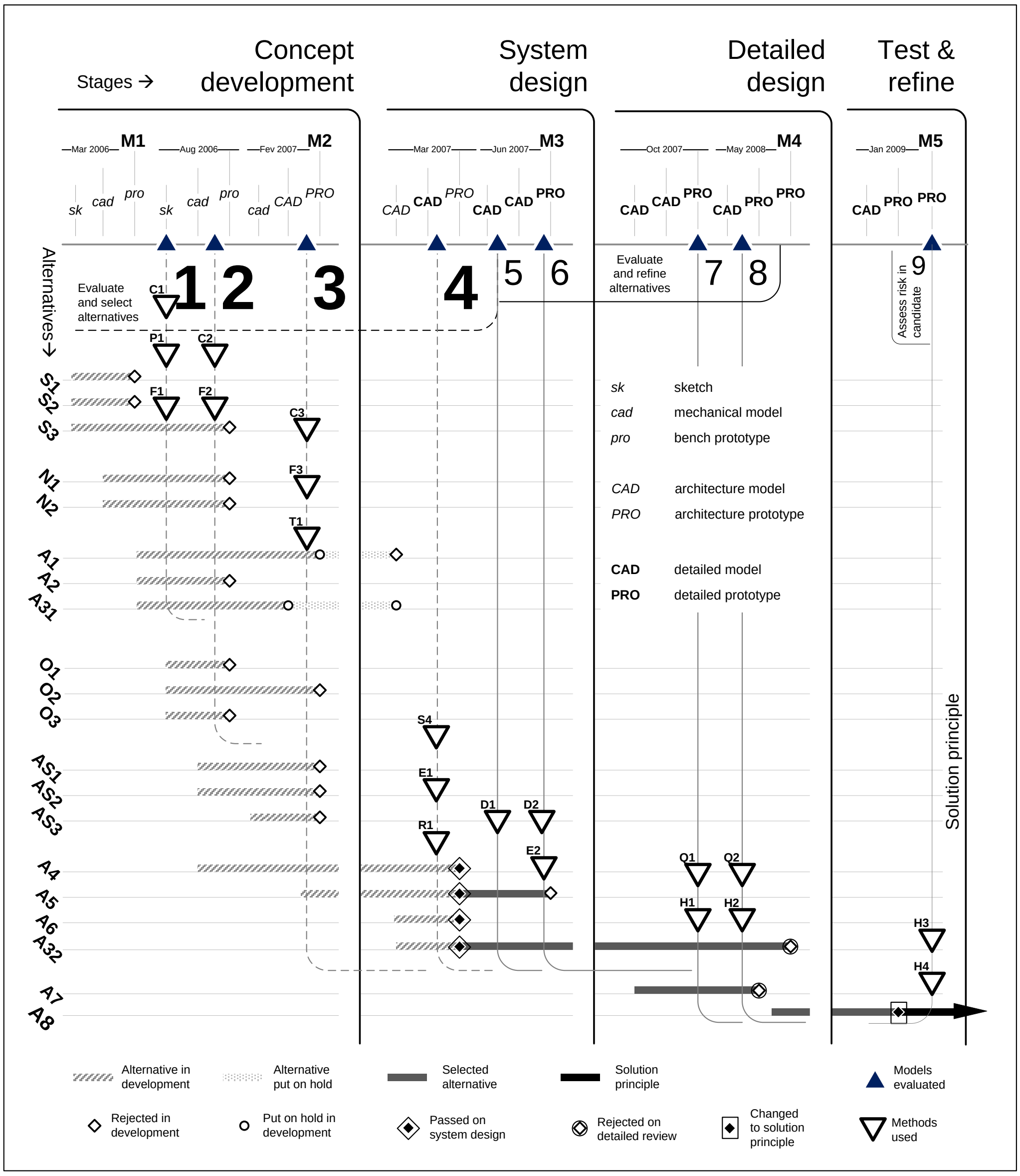

Figure 2 – Concept development timeline

R2: Influence of methods on the identification of failure modes

Milestones 1 to 4 emphasized design feasibility and confidence in meeting requirements, supported by brief tests on design models. A prescriptive use state diagram constituted the single instance of hierarchical or function/flow-based system representation found among documents. Alternatives from very early stages, up to A31, are affected by the following causes of rejection: 5 safety failures (one primary), 4 reliability failures (one primary), 7 robustness failures, and 4 integration failures. The following patterns are detected: a single secondary cause of rejection occurs several times (backlash) without association to working principle; a single primary cause of rejection occurs several times due to reusing similar interfaces; and a single cause for rejection has repeated occurrences with reusing the working principle. Safety failures were diverse, while robustness, reliability and integration failures were mostly due to the same problems.

Figure 3 shows the failure modes in design alternatives, which are assigned where they occurred and categorized on the design attributes affected. Alternatives are shown in the horizontal axis, with failures to rejection categorized on design attributes in the vertical. Design alternatives from early stages up to A32 are affected by: 8 safety failures, 8 reliability failures, 5 robustness failures and 4 integration failures. The following patterns are detected: two primary causes of rejection (safety) are repeated at least once due to reusing the same working principles; three secondary causes of rejection have the same problem of reusing the same working principles; and two other secondary causes for rejection occur several times without association to working principle.

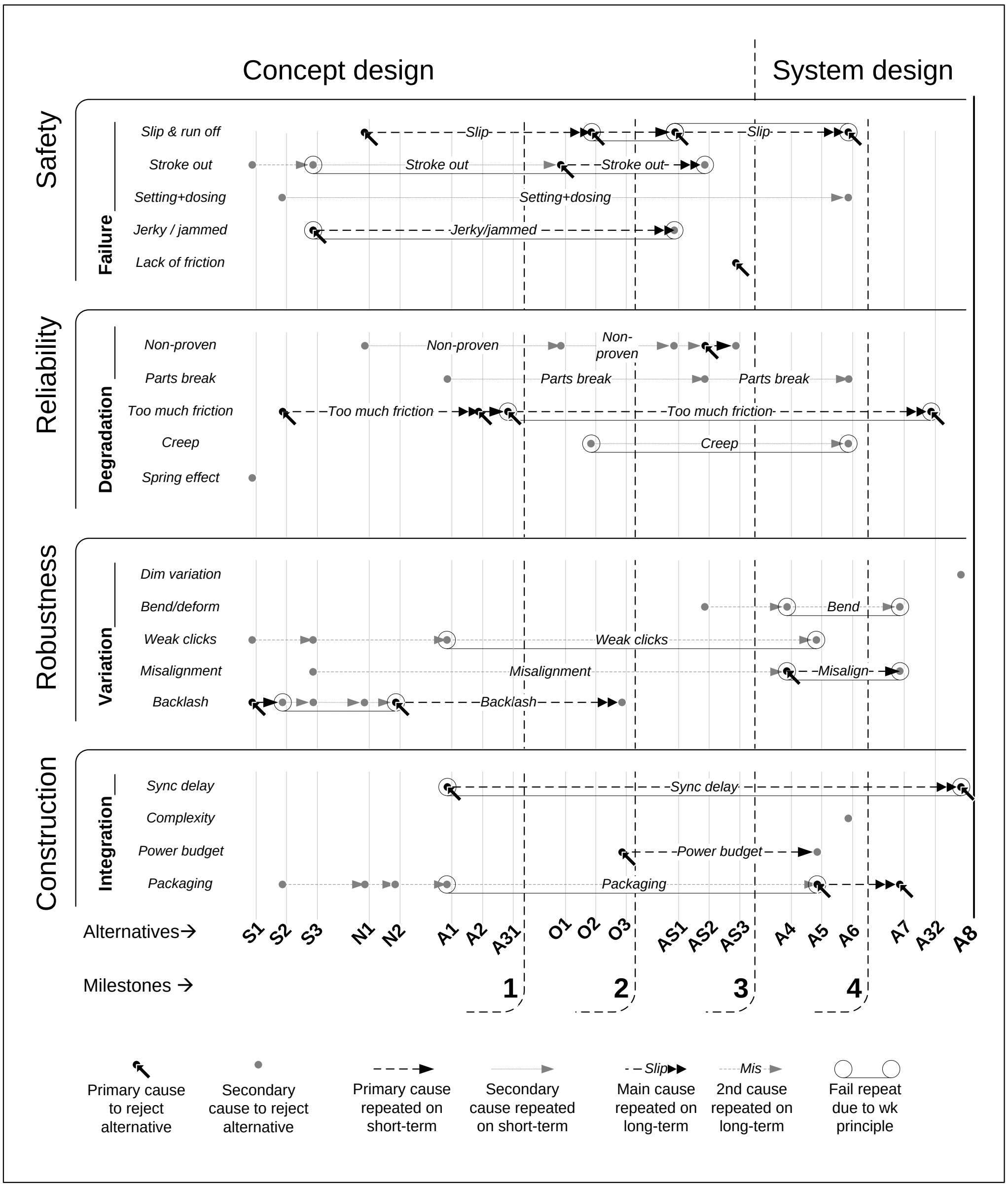

Figure 3 – Failure modes causing design alternatives to be rejected

Several failures affect all attributes considered, with reliability failures occurring more often on functionality (non-proven) and integrity (parts break) concerns. Along with safety, it becomes a primary cause of rejections due to many repeated occurrences with link to working principles. Other earlier robustness failures are repeated without link to working principles. As result, causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles throughout design iterations. That is due to current R3 methods lacking support to identify and pinpoint problems without evidence from detailed embodiments.

R3: Technical risk feedback from failure modes

Figure 4 shows the project stages in the horizontal axis, and the issues of concern to design attributes in the vertical axis. Arrows show how these issue groups evolved through concept development, on whether the issue has become more important (continuous double arrow), less important (long-dashed single arrow) or kept the same rank (short-dashed single arrow). In the earliest stage (M2), robustness issues were the most important. Feasibility was given a score of 4, with additional two points for the ‘not ready’ issue. Integration (5 points) and reliability (4 points) were also considered relevant. No safety concern was found in that stage. Feasibility is the most important concern, reflecting the need for a solution that can embody all expected functions. Reliability also needs development because there is uncertainty on how the expected functionalities will be embodied. Safety is a missing concern due to the lack of evidence on harmful performance.

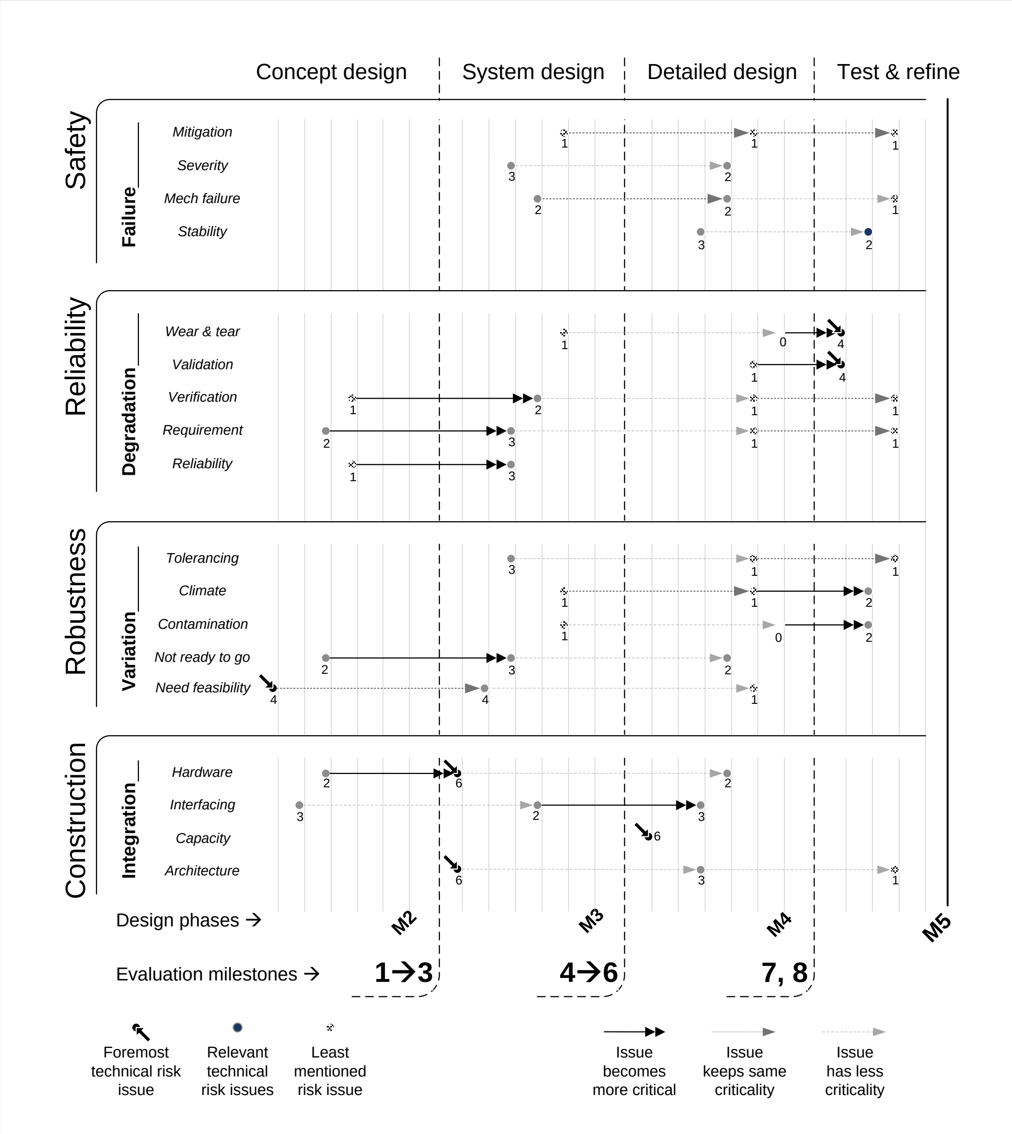

Figure 4 – Design feedback on technical risk issues and their behaviour over development

By the following stage, with alternatives undergoing R1 evaluation, integration issues were brought to the top (14 points). Robustness is the second relevant concern in this phase, with 12 points. The importance of reliability concerns increases in this stage (9 points). And safety concerns appear for the first time (6 points). System architecture is a new relevant concern in integration. The appearance of environmental factors causes renewed interest on robustness. Reliability is increasingly related to verification of requirements, with consciousness about wear and tear. Safety concerns first appear on the availability of evidence about harmful effects of performance.

Stage M4 increases focus on integration (14 points on capacity and interfacing), with robustness (4 points) and reliability (3 points) demoted. Safety grows in importance with new stability concerns (8 points); and stage M5 sees integration issues mostly solved (1 point), with renewed interest on robustness (5 points) and significant focus on reliability (10 points) with focus on long-term performance and its verification. Safety is demoted, with 3 points in the last stage.

Feedback on safety is absent in early stages, and appears only during system design, with increase in robustness and reliability. Design feedback issues were mostly found in early alternatives, as component-related generic attributes/problems that do not clearly indicate how to pinpoint and solve them. These conclusions confirm the lack of clarity of design feedback in early stages, due to the lack of resources that express enough knowledge to indicate strategies and measures to locate and solve the failure modes occurring in early concepts.

5. DISCUSSION

This section aims to discuss these results in the light of current knowledge and experiences. R3 methods were used to characterize design alternatives against perception, insight and preference of designers. They could identify failure modes quite early due to an all-out prototyping strategy on low prototype costs. However, causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles throughout design iterations. Motivations and causes for feedback issues are not specified in the project, and issues are characterized as component + issue tags. Similar studies in literature constitute basis for comparison, as shown in Table 2.

Table 2 – Implications from results in this study and other industries

Industry/ref.	Medical [this]	Automotive [25,37]	Oil & Gas [28]	Chemical [17]
Size, no. parts	Small, n x 10^1	Medium, n x 10^3	Large, n x 10^4	Large, n x 10^2
Complexity	Low	High	High	High
R3 dependency	High	Medium	High	High
Focus area	Eng. Design, DFx R3	Product development	Eng. design, safety	Eng. design, process
Duration	36 months	6 months (interviews)	6 months (interviews)	38 months
Methods and frameworks to R3 issues	Lack of R3 methods to novel concepts; current tools based upon insight and perception.	Current R3 methods and frameworks [16] support adaptive designs; lack of support to novel designs	Current R3 methods work on front-end engineering; new tech needs experimentation	Weak spot techniques as in earlier editions of [4], insight on divergence and convergence
Available models with evidence	Bench CADs and prototypes in early stages; detailed models from system design	Same approach as in our case, with early body models supporting plans for further stages	Detailed CAD models, math-based simulations of partial structures, equipment	Overview schematics, CAD drawings with relevant assembly components
Architecture strategy of development	Integrated modular architecture from 2nd iteration; models with all functions	Platform and modular architecture from onset, several modules linked by common connections	Single modular architecture tailored for each customer, models with some functions	Integrated architecture, custom reactor vessel surrounded by on-shelf components
Evaluation and testing of alternatives	Brief tests on generic parameters, working principles earliest evaluated on tolerances	Single-domain (FEA) tests on partial modules linked by reciprocity on boundary conditions	Single- and multi-domain simulations on partial modules linked by reciprocal conditions	Math calculations and simulation of design parameters, components on individual factors
Sources and criteria for decision	Brief reviews performed by the team, criteria defined by interpretation of customer needs	Detailed reviews with FMEA-like approach, criteria from detailed trade-off analyses	Hazard identification and probabilistic risk assessments with network models, FEA	Morphological matrices, criteria defined by overall design requirements
Feedback mechanism on selection	Communicated mostly in generic terms, pursuit of further alternatives by exploring issues	Communicated mostly in generic terms, pursuit of further alternatives by exploring issues	Specific feedback on the single module tested, change/adaptation is then pursued	Design frozen after conceptual design, changes on individual issues upon embodiment
Discussion of results	**System approach to pinpoint problems, knowledge reuse needed to focus intended outcome**	**System/platform in use, supported by KBE: no alternative for early stages/new technologies**	**System approach with probabilistic methods, knowledge transfer needs development**	**Functions are carried/ represented by parts, no option to reuse/transfer knowledge**

In other examples as shown in the previous table, mass volume manufacturers appeal to standardizing technologies; automotive and oil&gas industries use modular architectures from the onset, to decompose work packages and to add flexibility against R3 issues. Most sectors use simulations like FEA and CFD on partial modules, coupled by common boundary conditions. And feedback is mostly given in an informal manner, without capturing knowledge to further alternatives and/or projects.

The following circumstances should also be acknowledged: Oil&gas and chemical industries do not build and iterate design alternatives as in set-based development; and these sectors plus automotive also use historical data and Monte Carlo inputs to carry out non-deterministic risk assessments on detailed FEA and network models. However, these resources cannot be used to approach novel problems from the onset, which was our case. Design principles could be used as alternative, but they are too context-specific and do not solve the need to share design knowledge to get innovations accepted. In response to such needs, knowledge transfer and reuse should be the best resources assisting early design stages, because there is not enough evidence and/or data to use probabilistic network models of FEA simulations to solve R3 issues.

6. CONCLUSIONS AND FUTURE WORK

This paper aimed at understanding the following issues in conceptual design: diagnose of design flaws; how they influence design feedback; and how the issue can be improved in early design stages. The work has been carried out by the means of a longitudinal case study following the development of an insulin pen. Results were obtained in the following areas: the lack of R3 evaluations during early design stages is confirmed; causes of rejection of earlier alternatives are repeated in later designs due to reusing working principles; and, design feedback lacks clarity in early stages, stated in a generic manner when present. Recommendation is given to incorporate design insight and knowledge to any approach to support concept development. Future work involves developing a knowledge-based tool to help design decisions and feedback, and the validation of scenarios considering failure modes, benefits and countermeasures.

7. ACKNOWLEDGMENTS

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Definitions: **HAZOP**: Hazard and Operability Studies; **FTA**: Fault Tree Analysis;
FMECA: Failure Mode, Effects and Criticality Analysis
DFMA: Design for Manufacture and Assembly

It will be a pleasure to address your questions,

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DECISION-MAKING AND FEEDBACK AS FOCI FOR KNOWLEDGE-BASED STRATEGIES SUPPORTING CONCEPT DEVELOPMENT

V. K. Marini, S. Ahmed-Kristensen

Keywords: decision-making, design feedback, concept development, risk, robustness,

1. Introduction

Performance attributes of the product, such as robustness, reliability and safety are widely acknowledged as relevant considerations through the design process. Yet they are more important in early design stages to ensure the feasibility of design requirements and reduce later design rework in the product lifecycle. This influence is due to the available room for making decisions, together with the cascading effects of these through downstream design activities [Andreasen & Olesen, 1990].
Prior studies revealed the incompleteness of information from early stages for using current methods for robustness, reliability and safety, which also confirmed the problem of the extensive resource requirements in their use [Marini, Restrepo & Ahmed, 2010]. In response to this conclusion, a longitudinal study was performed in collaboration with the manufacturer of an insulin injection pen. This study followed the development of 20 solution alternatives for a new design of such device.
This paper aims to describe the influence of design decisions and feedback originated from failures in solution alternatives during the concept development activity. It identifies the characteristics of the development process that influence practices in decision-making and feedback, and it discusses strategies to evaluate and mitigate failures in solution alternatives.

2. Background

This section presents the background for this study, comprising of engineering design knowledge management, and risks during concept development. Descriptions of the design process provide generic overviews on the design process [Pahl, Beitz, Feldhusen & Grote, 2007]; or they emphasize different views on engineering design activity: for instance, guidance to management as a nesting, multi-faceted set of activities [Hales, 1993], and prescriptive methodologies to evaluate and verify a design, with focus on dealing with variation [Yang & El-Haik, 2006]. Product design considerations need to accommodate competitive needs. Multiple-technology and multi-domain designs, and the need for their fast integration, have given birth to product architecture considerations [Ulrich, 1995]. Modularity has particular importance, as it influences development management, design flexibility and product performance [Hölttä, Suh & De Weck, 2005].
Considering the variety of solution alternatives and the uncertainty of their satisfying design requirements, concept development becomes a situation subject to uncertainty and ambiguity [Schrader, Riggs & Smith, 1993]. This escalates on the lack of awareness of designers about the knowledge which is available to them against the information requirements to assess and manage technical risks, which is only mitigated by experience [Bracewell, Ahmed & Wallace, 2005].

Uncertainty and ambiguity pervade through the design process, cascading from the comparison of requirements against customer needs toward the development of a design solution with the aim of satisfying such requirements [De Weck, Eckert, & Clarkson, 2007]. The common reuse of past designs intuitively performed by engineers is understood to mitigate the uncertainty in novel developments, but may increase the ambiguity from conflicts in changed interfaces [Eckert, Stacey & Earl, 2005].
The occurrence of failures is linked to the lack of scrutiny on solution alternatives, and the lack of awareness to the losses from past mistakes [Petroski, 1994]. Four types of impediments preclude failure prediction: too much effort to process information, bias to avoiding commitment, isolation and lack of coordination, and lack of confidence on methods [Busby & Strutt, 2001]. A major issue to assess and manage risks throughout the deisgn process concerns methodologies that allow teams to build shared understanding of risks and uncertainties [McMahon & Busby, 2005].
Experience plays a significant role when designers make references to prior facts they were told by their peers or experienced themselves [Visser, 1995]. Designers engage in branching out issues and alternatives in decision discussions: criteria are updated along the emergence of situations, while previously considered factors may be forgotten upon this evolution [Dwakaranath & Wallace, 1995]. Other characteristics of design decisions consider: short time given to discussing the importance of criteria; and little influence of formal methods on justifying the evaluations [Girod et al., 2003].

3. Knowledge strategies in the design process

This section presents the classification of design knowledge, the representation of design with models, the capture of design rationale, and the recognition of heuristics in design models and designers' behaviour.
Design knowledge is classified in different types through ontologies, in order to facilitate the acquisition and retrieval of design information by indexing mechanisms [Ahmed, 2005]. The derivation of these ontologies is to be carried out through empirical research with the aim of extracting generic types from information specific to individual design projects. Current knowledge in literature provides a basis for establishing prior definitions for the intended classification; this is complemented by the extraction of novel types from empirical data and their validation in dialogue with users [Ahmed, Kim & Wallace, 2007]. A taxonomy for robustness, reliability and safety issues in product design attests the effectiveness of this framework in approaching complex issues, such as the evaluation of information requirements in current methods for robustness, reliability and safety [Marini, Restrepo & Ahmed, 2010].
Design rationale consists of relevant knowledge about the reasons designers define for engaging in specific courses of action through the design process. The capture and development of design rationale starts from generic frameworks guiding the identification and treatment of design issues toward recording decision chains for later retrieval and playback [Nagy, Ullman & Dietterich, 1992]. This approach is implemented with a design rationale recording tool, DRed, that departs from a simplified issue-based framework to implement a fully functional design rationale tool that records the discussion of issues to defining conditions of further action [Bracewell, Ahmed & Wallace, 2004]. A simplified approach based on sketches and interconnected statements about concept-configuration-evaluation triplets [Kroll & Shihmanter, 2011] captures design rationale generated during concept design.
The use of heuristics consists of extracting 'rules of thumb' and strategies from observing models and activities in the design process. The meanings of visual and behavioural signs extracted from design models are then translated to guidance for designers when engaging with problems. One significant instantiation is the definition of design principles extracted from long-term experience [French, 1992]. This approach is applied to modelling with the suggestion of heuristics for the modularization of product architectures starting from functional system models [Stone, Wood & Crawford, 2000], which are recognized from the graphical interpretation of function structure models. Other way to use heuristics is to follow expert behaviour and recognize strategies that can be applied in order to improve communication among designers and solve design issues [Ahmed & Wallace, 2004]. A fuzzier use of heuristics takes place when extracting design attributes of good examples as 'rules of thumb' to generate better solutions [Fu, Cagan & Kotovsky, 2010].

3.5. Our conclusions

Most propositions for engineering design address the engineering design tasks as the context of their use. They give support to engineering design in form of prescriptions and strategies to modelling solution alternatives and evaluating their performance. In our view, Knowledge management solutions have already been successfully applied to engineering design in order to support leveraging the intellectual capital inside manufacturing organizations.

However, current processes of concept development are still surrounded by uncertainty and ambiguity as the understanding about the intended solution is at best approximate and incomplete. Little scrutiny of solution concepts, attitudes that preclude failure prediction and the lack of methodologies to build common understanding about risks affect proper decision-making towards reducing technical risks. While knowledge management solutions work well in supporting the design task, there are significant issues: in the one hand, their effective use in decision-making is at best elusive as their support focuses the long-term design activity in modelling and generating knowledge; in the other hand, approaches for decision-making tend to focus on making records about the decision process rather than actually assisting designers, and taking advantage from their knowledge.

4. Research method and aims

This study was performed as an investigation of opportunities to improve the ability in managing technical risks during early design phases. This study aimed at finding out how current practice imposed obstacles to solving problems in regard to the attributes of robustness, reliability and safety in solution alternatives. The insulin injection pen is characterized as a precision-mechanics device integrated with electronic components whose performance is especially sensitive to robustness, reliability and safety attributes due to the life-threatening implications from performance shortcomings regarding the application of insulin in diabetic patients.

The study was performed as a longitudinal case study [Yin, 1994] with the objective of investigating complex relationships in the use of design information to evaluate robustness, reliability and safety attributes and their implications to the course of action in concept development. As its objective is to find out and describe shortcomings with current practice in concept development, it can be understood as a first descriptive study within the design research methodology [Blessing & Chakrabarti, 2007].

The research approach consists of collecting retrospective data about 36 months of concept development activity for developing the principle solution for the new device, along with interviews to explore the context and validate the findings on the information about the project. Four data collection approaches were used: document analyses, reverse engineering [Otto & Wood, 1998], interviews (open-ended and semi-structured) and modelling/representation. Their use throughout the project is summarized in Table 1.

Table 1. Longitudinal case study [Marini, Ahmed-Kristensen & Restrepo, 2011]

Characteristics	Document Analyses	Reverse engineering	Interviews with designers	Modelling and representation
Case executed with actual project	17 partial/closure stage presentations	4 sketch sessions of work principles	5x open-ended on R3 development issues	9 function modules in all alternatives
Researcher observes project	5 technical risk stage reviews	20 alternatives of solution (concepts)	3 mechanical engineers, 1 system engineer and project manager	Several overview and close-up screenshots of alternatives
Longitudinal and retrospective study	14 feasibility reports on features	50 CAD variants with small changes	Not mediated, with video records. (45min each)	3 sequential/timeline development graphs
Comprehensive study of situation	4 matrices about set-based dev.	9 modules in system formulation	3x semi-structured on concept selection decisions	Total of 50 failure occurrences to reject
36 months from sketch to solution	Several reports from evaluations	61 work principles in all alternatives	Mechanical engineers: 2 veteran, 1 expert; Risk specialist	Total of 47 mentions to technical risks
Lead time launch in 6 to 8 years	Validated by interviews	Associated to interviews	Specialist as mediator, with video records (60 min each)	Developed upon interviews

Document analyses were carried out through the whole case, to understand when concepts were generated, which models were developed, which issues took place and when concepts were discarded. Reverse engineering was used to identify the functions performed by design alternatives, their working principles and similarity between these. The project team was composed by the project manager, three mechanical designers (two veterans), one risk specialist, and three electronics engineers (one veteran). Open-ended interviews were carried out with all mechanical designers, one system engineer and the project manager. Semi-structured interviews were carried out with mechanical designers only. Questions asked focused upon two types of issues: challenges and measures to manage technical risk (open-ended), and the rationale for selecting and rejecting design alternatives (semi-structured), to guide the search for information and validate the findings from documentation and reverse engineering, respectively [Marini, Ahmed-Kristensen & Restrepo, 2011].

5. Results

The data collected during the study was analyzed to understand the general approach to concept development, the solution alternatives and their working principles. The relationships between the alternatives and the reasons for their rejection were examined in the data. The first result is the description of the concept development process as executed. The study followed the development of solution alternatives up to the final choice of solution principle, concerning the scope of the internal mechanism of the insulin injection pen.

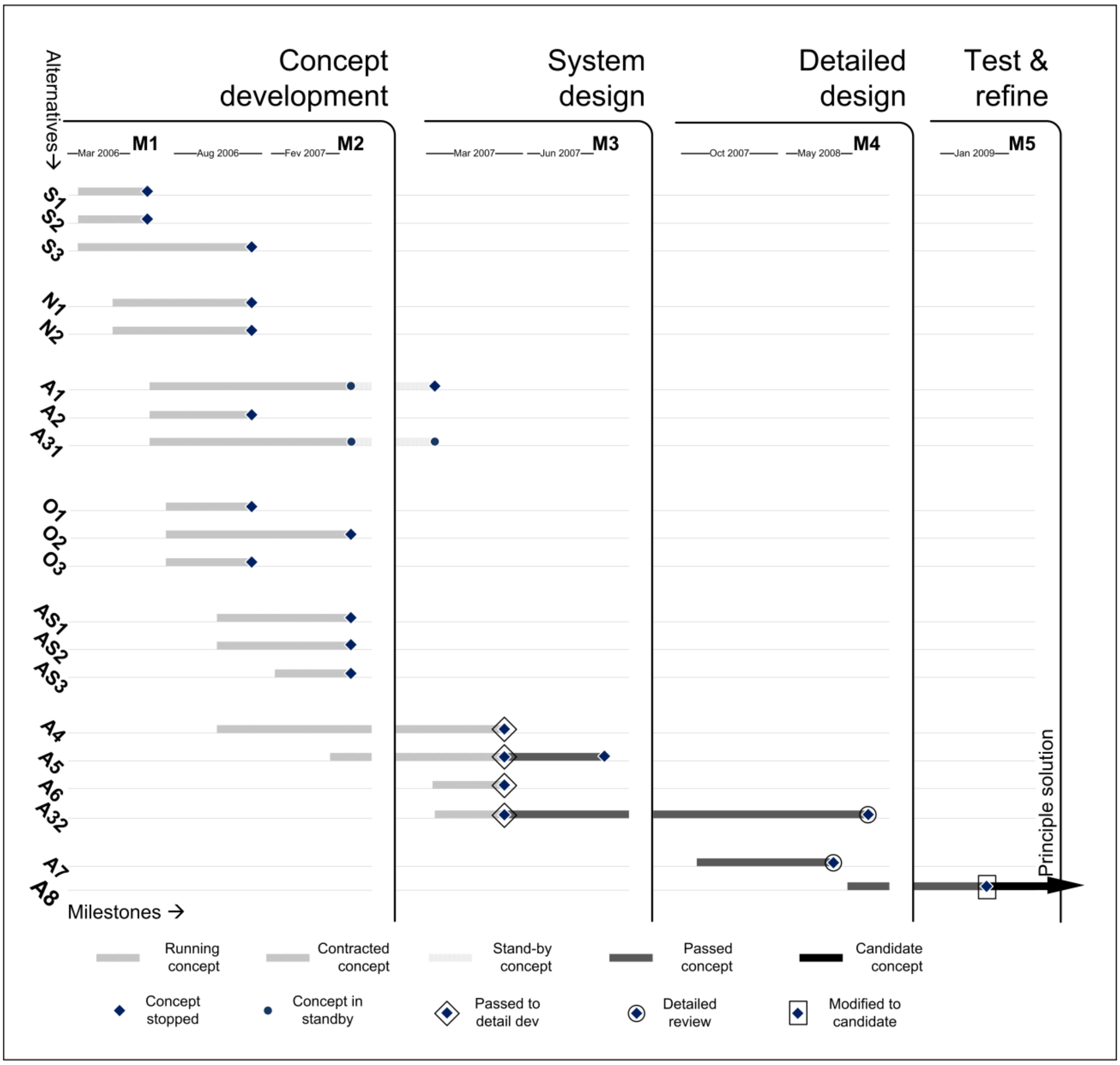

Figure 1. Development of solution alternatives

Figure 1 shows the phases and stages (Mx) for the development of solution alternatives of the medical device, from concept development up to testing and refinement, when a principle solution was selected. The developed alternatives are shown in the vertical axis, with the design stages shown in the horizontal axis. The legend in the figure indicates the development states of alternatives and the milestones of alternatives being rejected, put on stand-by, and passed.
The first phase, concept development, concerns the implementation of working principles and their integration in alternative mechanism formulations. These provide approximate descriptions of working principles and of their physical implementation in product architectures. In that context, their development focuses issues regarding the performance of mechanism designs in order to minimally satisfy design requirements. The development of alternatives is shown to continue through system and detailed design, which indicates the negotiation of interfaces between system functions.
That reflects the adoption of a set-based approach [Ward, Liker, Cristiano & Sobek II, 1995], where solutions are explored and refined through a long period. Designers continuously negotiate design interfaces up to reaching agreeable strategies and converging values to establish the solution principle. Later alternatives are developed with increasing detail, reusing working principles used in previous alternatives. If some of them are rejected, new alternatives are designed with variations in architecture and changes in working principle. The changes in working principles reflect an exploration of possibilities in regard to satisfying requirements on given system functions.
The second result is the description of reuse and variants of working principles in solution alternatives. The study has obtained knowledge about the reasons to reject solution alternatives by interviews with engineering designers, performed when the solution principle was being refined.
Figure 2 shows the the variety of working principles that was used and reused in solution alternatives, compared against the reasons found for the rejection of solution alternatives. The developed alternatives are shown in the horizontal axis, with the reasons to reject and the variety of working principles shown in the vertical axis. The occurrence of failures and the reuse of working principles are represented with arrows, with repeated failures are highlighted in red.
The figure shows that variety of working principles in adjacent functional units was found to be the highest in proportion to the complexity of function units in their number of physical interfaces. The Actuate displacement unit was found to have an average of eight interfaces through solution alternatives, and the export medicine unit was found to have an average of three interfaces. In that regard, the variety of working principles increases with the number of physical interfaces, as there are more degrees of freedom that need to be negotiated. Another characteristic found through the study was the repetition of reasons for rejection in parallel with the reuse of working principles from alternatives that were previously rejected for the same reasons.
While the reuse of past designs facilitates much of the design work as they incorporate knowledge which is already developed [Eckert, Stacey & Earl, 2005], it becomes a problem when different solution alternatives fail because of the same problem. The repetition of failures indicates that not enough knowledge was collected from previous decisions. This takes place as decisions are taken through the development process without clear enough information on their motivations. At the same tome as the available information enables designers to make decisions, repeated failures take place because of the failure to incorporate previous failure occurrences as feedback to further development work [Marini, Ahmed-Kristensen & Restrepo, 2011].
Repeated failures take place more often on function units that are more complex. This may be due to the fact that decision statements clearly described the performance failure that motivated the rejection of alternatives, but could not pinpoint where the failure took place or what was the issue so that to provide feedback to the development of further alternatives. The reuse of working principles that failed previously ended up consuming development resources that could be invested into implementing novel solutions from principles that worked well and needed improvement.
The third result consists in the identification of direct relationships between decisions on solution alternatives and the development of new ones. The study focused the development timing among solution alternatives, identifying the development of further solution alternatives from the need to create feasible options to implement the principle solution for the mechanism of the insulin injection pen.

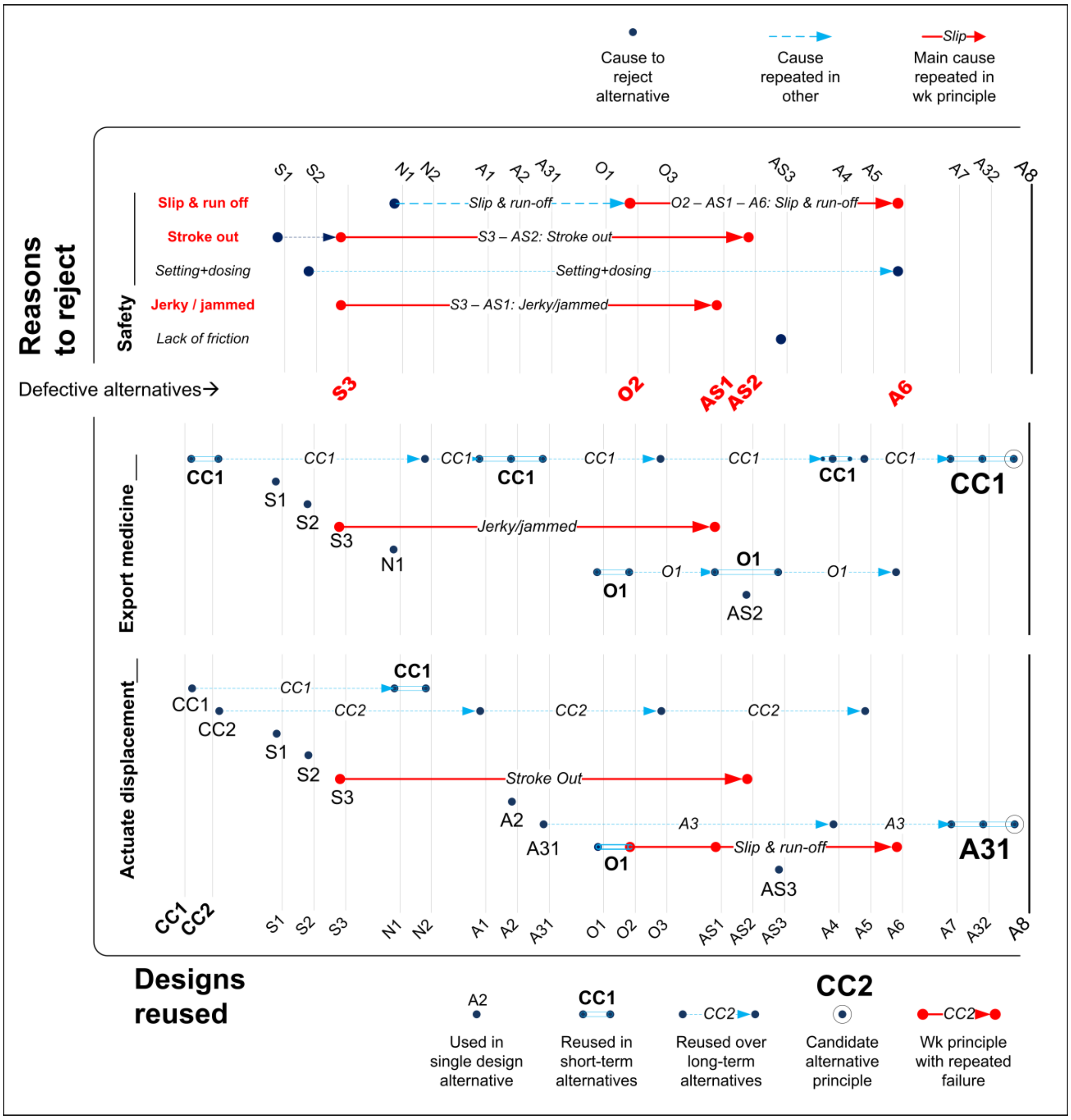

Figure 2. Reasons to reject alternatives and design reuse

Figure 3 shows the the development timeline highlighting the relationship between the rejection decisions and the generation of new alternatives. The decision-making milestones are shown in blue, while the generation of new alternatives is shown in red. The decision–feedback loops are shown in red dashed squares, and identified from A to G. The first phase in the project shows several parallel alternatives on the run, with three feedback loops (A, B and C), which is the same number of feedback loops in all other subsequent phases.

It was shown that evaluation methods in concept development influence decisions and feedback on solution alternatives [Marini, Ahmed-Kristensen & Restrepo, 2011], and this illustration confirms the strong relationship between decision-making and feedback. The results on design reuse shown in this paper indicate there is a shortcoming in taking advantage from decisions made to avoid the repetition of reasons for rejection in further solution alternatives.

That consists of the failure in decision-making and feedback to learn from the first occurrence of failure – data collected from the study show that such repeated failures are only definitely corrected upon their second or third occurrence among several alternatives. The issue with failing to pinpoint the locations of failure derives very much from the ambiguity among the product architectures of solution alternatives in regard to the parameters in working principles.

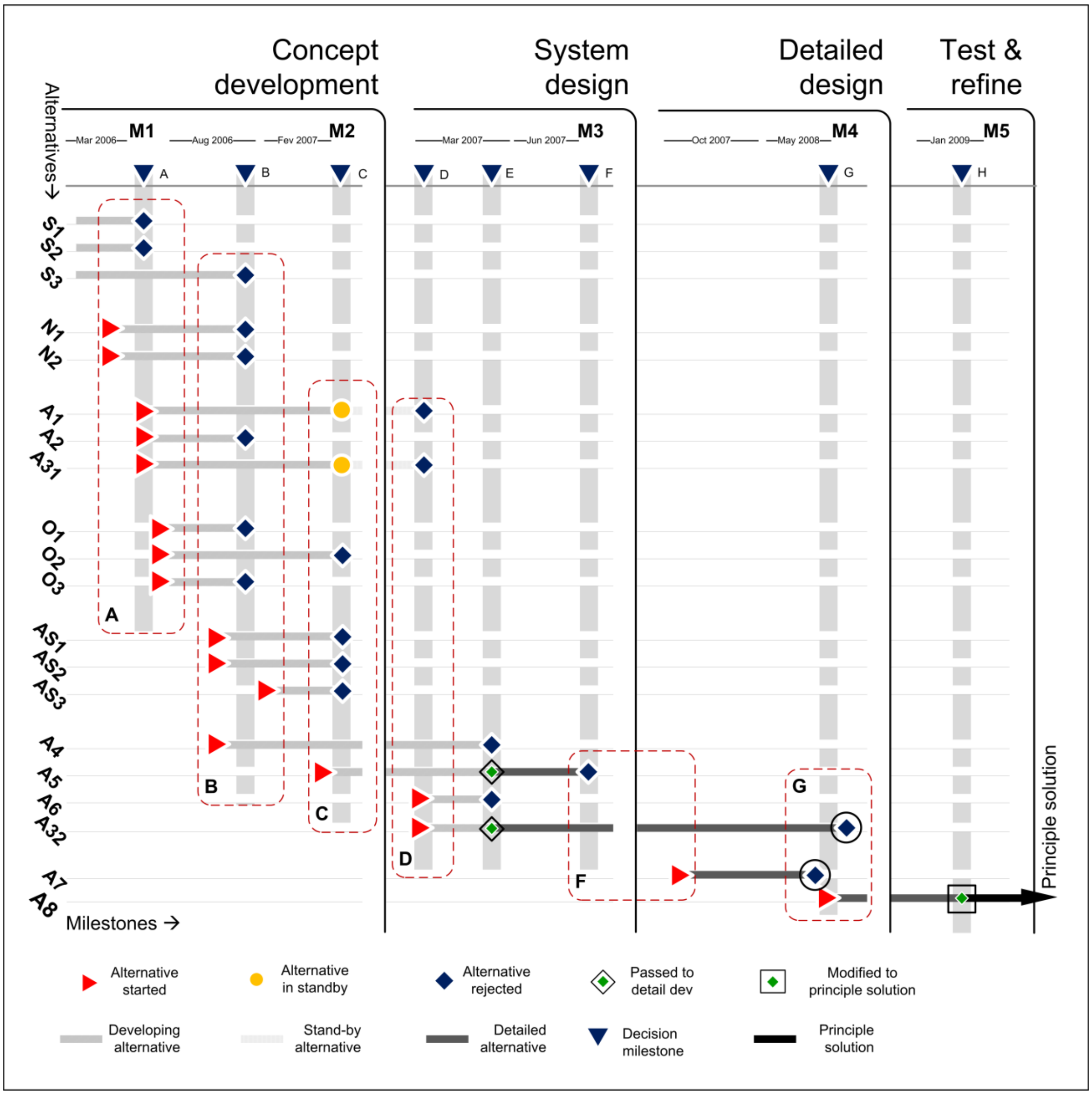

Figure 3. Design feedback among solution alternatives

It is difficult to make generic criteria applying to all possible variants, especially when they are to be compared at the component level. That generates the need for support to overcome such differences in comparing alternatives and identifying their failures [Schrader, Riggs and Smith, 1993]. The chain of decisions through the project shows that the decision criteria not only evolve through single meetings [Dwakaranath & Wallace, 1995] but mainly in the long-term through the evolution of issues in the design process.That takes place as the decision criteria evolve from a concept basis to a system basis. However, the study has shown that the reasons for rejecting solution alternatives stay mostly the same through early phases of the design process. That can be interpreted as result from overall functional and environmental parameters that make the general concept of the new design. These parameters operate at the technical process level, so they influence the kind of working principles that can be used. This could be used as cue to predict most of the issues with selected working principles.

6. Discussion

Current knowledge management approaches provide support to ongoing development tasks, but there is need to assess their effectiveness in supporting designers when they need to make decisions and take advantage from the knowledge they learn from issues in previous alternatives. Table 2 shows a comparison of approaches to identify and mitigate failures in product development. Set-based development is being increasingly applied through industry, as our case shows.

Table 2. Comparison of approaches to identify and mitigate failures in product development

Industry/ref.	Medical device	Automotive	Oil & Gas
Size, no. parts	Small, n x 10^1	Medium, n x 10^3	Large, n x 10^2
Complexity	Low	High	High
R3 dependency	High	Medium	High
Focus area	Eng. Design, DFx R3	Product development	Eng. design, process
Duration	36 months	6 months (interviews)	38 months
Reference	Marini, Ahmed-Kristensen & Restrepo, 2011	Ward et al, 1995, Shimizu et al., 2003	Busby, 1998
Management framework	Set-based development	Set-based development, *Mizenboushi*	Risk assessment, compatibility matrices
Modelling approach	Whole product, system mechanism: virtual and physical prototypes	Components, subsystems, virtual and physical prototypes	Subsystems, whole product, virtual prototypes
Knowledge platform	Expert knowledge	Expert knowledge, KBE	Expert knowledge, KBE
Failure identification	Measurement + simulation	Measurement + simulation + DRBFM	Simulation + FORM/SORM + HAZOP
Evaluation and testing of alternatives	Brief tests on generic parameters, working principles earliest evaluated on tolerances	Single-domain (FEA) tests on partial modules linked by reciprocity on boundary conditions	Math calculations and simulation of design parameters, components on individual factors

The use of set-based development expands the horizon of design alternatives further from concept development, toward alternatives to system and detailed design. The use of past designs is more sensitive to changes, where the *Mizenboushi* technique [Shimizu, Otsuka & Noguchi, 2007] works, with DRBFM (Design Review Based on Failure Mode) as carrier of design considerations. Risk assessment plus methods such as FORM and SORM (First, and Second-order reliability method) is mostly performed in the oil & gas environment, where any issue could be critical threatening the success of the operation. [Busby, 1998].

The involvement of designers through the product lifecycle determines the success in that effort. This is more critical at the decision-making process: there is lack of necessary information about critical problems; the information about the severity of most flaws (or the lack of it) does not justify their mitigation; and, there are doubts on whether the issues found make symptoms of flaws in product design [Gries, 2007]. While heuristic strategies and taxonomies have shown success with aerospace design [Ahmed & Wallace, 2004; Ahmed, 2005], there is more potential to evolve their application on other sectors, with significant role to support, discussion, decision and mitigation of design flaws.

6. Conclusions

Starting from a review of current knowledge about engineering management frameworks, support for knowledge management and issues in concept development and decision, this paper engaged in discussing the recognition of decision-making and feedback as core issues in the repeated failures observed during concept development. Results from a longitudinal study performed in collaboration with a medical device manufacturer demonstrate the need to support the evaluation of several options starting from concept design toward the choice of the principle solution, the failure of current practice to avoid the repetition of flaws in robustness, reliability and safety on solution alternatives, and the need to address decision-making and feedback with knowledge-based support.

Future work involves the development and validation of knowledge-based tools to address decision-making and feedback issues during concept development, considering the manifestation of design attributes and the use of such information by designers for decision-making and feedback.

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DRBFM – Design Review Based on Failure Mode
FORM – First-order Reliability Method
SORM – Second-order Reliability Method
FEA – Finite Element Analysis
KBE – Knowledge-based Engineering
HAZOP – Hazard and Operability Studies

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The use of engineering knowledge for the evaluation and the selection of solution alternatives during early design phases

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Abstract

This paper addresses the use of engineering knowledge to address robustness, reliability and safety attributes of solution alternatives as bases for decision-making through early design phases. This study aims to elucidate the interaction between the use of engineering knowledge and the implementation of product development strategies. For that purpose, a longitudinal study was performed in collaboration with industry, to analyse information on the development of an insulin pen mechanism, and to assess the influence of engineering knowledge towards the principle solution. The complexity of individual functions in interfaces and degrees of freedom led to developing a wider variety of working principles. Also, the rejection of several solution alternatives because of design issues manifested by previous designs hinted to the unintended reuse of failed working principles for individual product functions. Then, the inconsistency between failure mechanisms and directions for improvement resulted in divergence between design decisions and feedback. The following factors were then identified: increase in the variety of working principles needed to negotiate interfaces and degrees of freedom; lack of clarity about constraints in prior working principles and ambiguity about conflicts from their reuse; priority shifts through decision-making and feedback due to development in design detail and neglect of constraints upon reuse; and, the failure from design feedback in informing designers the conditions for the reuse of working principles. This situational framework allows the conclusion on the lack of support to the use of engineering knowledge for design verification in the basis of confidence.

Keywords

Robustness, reliability, safety, concept design, design reuse, set-based design

Introduction

Industrial companies aim to maintain and strengthen their position in the market, by developing innovative product designs that will enable them to make and share new profits. In this context, engineering knowledge in early phases underpins the work of design departments in establishing key design characteristics that will win the favour of their customers. Commitments in the early phases of design process are critical to project execution during product development, as major parts of the project budget are determined in the initial stage (Andreasen & Olesen, 1990). New market opportunities motivate the development of new designs, due to novel requirements that current designs cannot meet. At the same time, design teams are required to evaluate concepts under conditions of significant uncertainty and to make short-term decisions due to the tight project schedules. These conditions determine how design teams must use strategies and procedures to raise issues, clarify ambiguities and progress in a project. Hence, it is necessary to improve the use of engineering knowledge to support the verification of the feasibility of innovative designs, and to decide on a principle solution in accordance with the design requirements for the ongoing project. Practices in product development that help to exploit and manage engineering knowledge drive research efforts in the following areas: strategies to deal with novelty and uncertainty in product development; and methods to support the functional verification of concepts in engineering design.

Research work in the area of product development aims to explain the strategic choices involved in developing solutions in design projects (Clark & Fujimoto, 1989). This area explores issues related to the management of the overall product development project in such a way as to improve efficiency in budgeting, lead time and quality. In this context, authors explore ways of anticipating interaction between organizational areas and exchange information (Takeuchi & Nonaka, 1986) so as to hedge and respond to challenging issues and reduce the potential lead time in product development. Research work in the field of engineering design on the verification of design functionality aims to generate insight about the factors that influence the way designers get aware about design issues, and to enhance the methods and forms of reasoning that designers use to implement engineering solutions (Cross, 1993; Pahl & Beitz, 1996). This field explores ways of eliciting and modelling characteristics of product design that enable designers to think about and solve engineering problems. With this purpose, the authors focus upon the development and evaluation of methodologies for solving engineering problems, with focus on the methods used, the lines of reasoning and the consequent courses of action.

This study concentrates on the interface between the choices of strategies for developing the principle solution and the use of design methods to verify solution alternatives during concept design. One aspect in particular that mediates this interface is the use of engineering knowledge in design practice (Ahmed, Hacker, & Wallace, 2005). For instance, effective problem-solving depends upon the use of engineering knowledge by designers to select the information they need for engaging and fulfilling design assignments (Court, Ullman, & Culley, 1998), and upon the consequent courses of action that designers employ in order to tackle engineering problems. Such requests for information trigger a chain of knowledge consolidation regarding how design issues are handled, distributed and solved. This highlights the relevance of engineering knowledge management as a research subject, as it deals directly with the motivations and mechanisms employed to deal with engineering problems that are crucial for the implementation of product development strategies. Within this area, this paper aims to elucidate the implications of the use of engineering knowledge towards the implementation of product development strategies that determine the outcome to R&D projects.

This paper presents results from a case study that followed an R&D project generating 20 solution alternatives for the principle solution of an insulin injection pen, which was to be further developed for mass production. It focuses the use of information about robustness, reliability and safety attributes to develop novel designs, as example of the interaction between strategic and tactical considerations in product design projects. While prior research provides proof of the influence of uncertainty in product development projects (Pich, Loch, & De Meyer, 2002), questions remain on the following aspects of engineering design practice:

- how design issues are elicited for the decision process; and,
- how the feedback from verifying these is incorporated into the intended strategy.

Prior studies of our own revealed the shortage of information from early design phases for the use of current methods for robustness, reliability and safety (Marini, Restrepo, & Ahmed, 2010). The influence of the information required for current methods for functional verification in evaluation tactics and development strategy remains a question in regard to experimentation and prototyping (Thomke, 1998; Ulrich & Eppinger, 2002), and is a relevant subject within the engineering design domain as design methods and engineering knowledge are still explored in a separate manner (Culley & Clarkson, 2005; Ahmed, Hacker, & Wallace, 2005).

This paper is divided into the following sections: background knowledge presents the current level of knowledge within the academic world on the topics related to the problem approached in this paper; research approach introduces the procedure used for extracting and processing the data from the study so as to attend to the proposition of this paper; results from study presents the outcome of the study as it demonstrates the issue which forms the topic of this paper; discussion of results debates the results obtained in relation to recent developments in the same field; and, conclusions reflects on the contribution represented by the results of this study.

Background

Product development strategies are employed by project managers and implemented by design teams, to develop a design based on knowledge of requirements, issues and their dependencies. These strategies are relevant to product development because their use can add value to e. g., quality and time-to-market (Hauser & Clausing, 1988; Clark & Fujimoto, 1989). These examples show how practices and strategies are used in order to attain desired attributes in the product and desired outcomes in project execution. In the concurrent engineering framework for product development, design lifecycle stakeholders are included in multidisciplinary team management strategies for product development tasks – in contrast to their absence in traditional practices (Takeuchi & Nonaka, 1986). Along with the development of coordination strategies for product development management, product design considerations need to change in order to accommodate new competitive needs. Product architecture is also of concern to address the need for fast integration of complex multiple-technology and multi-domain designs (Ulrich, 1995). Such developments allow the implementation of concurrent and continuous engineering feedback as developed and performed in industrial practice, where problem-solving cycles overlap by early information exchange between engineers and smaller innovation leaps in new projects.

Another view on development strategies consists of modelling product development projects as processes, thereby suggesting ways of acquiring and processing information about the design being developed. This can be proposed in two different levels: modelling the succession of tasks needed to design a product such as with Systematic design (Pahl & Beitz, 1996); or, proposing tasks to which specific approaches are recommended, as prescribed by Design for Six Sigma (Yang & El-Haik, 2003). These approaches influence the selection of methods for eliciting information about product design attributes, to verify developing designs regarding their functional parameters and their suitability to design requirements. Models of the design process are proposed in form of an overview of the tasks and considerations that are needed in order to process the input from market into compelling and feasible designs (Hales, 1993). This is because real development processes undergo a complex network of relationships that is difficult to depict and, even if depicted, difficult to follow. There is difference in emphasis across these frameworks, in which the process model approach (Systematic Design) emphasizes the development of product functions whereas the task method approach (Design for Six Sigma) favours the verification of product functionality (Stauffer & Pawar, 2007).

A principal factor affecting the execution of development strategies is the need of knowledge to generate a feasible principle solution of the product being designed. This is especially critical in early design phases, owing to the variety of alternatives that can arise from a creative process; this may occur together with lack of knowledge about the best possible outcome that can be achieved. These issues mean that concept development is a situation subject to uncertainty and ambiguity in decisions (Schrader, Riggs, & Smith, 1993), which are pervasive through the design process as they flow through from the comparison of design requirements against customer needs toward the development of a design solution (De Weck, Eckert, & Clarkson, 2007). In such situations, there is a beneficial relationship between past designs and design projects: on the one hand, existing designs eligible for reuse allow variations of use and efficiency improvements (McMahon, 1994); on the other hand, reusable designs offer 'templates' that facilitate the generation of new content for ongoing design tasks (Eckert, Stacey, & Earl, 2005). Strategies for design reuse aim to influence design practice towards increasing the reuse of precedents in engineering organizations. The preservation of past knowledge from experience is complemented by the obtaining tolerance to past solutions in new problems and creating opportunities to apply past solutions in order to solve new problems (Busby, 1998).

This mechanism constitutes the core of strategies for improving efficiency in product development with focus on communication. As a product development strategy, set-based development follows three basic principles (Ward, Liker, Cristiano, & Sobek, 1995):

1. design feedback is anticipated to be in parallel with the generation of alternatives, and carried out as a continuous process since early design stages;
2. designs for different subsystems and development stages are continuously fine-tuned and fit to each other up to a late design freeze; and,
3. the development process includes continuous verification of mutual and conflicting constraints for adjustment.

Set-based development takes advantage of such principles to implement design verification by iterating and continuously applying the following steps:

- Firstly, a single design team verifies a variety of alternatives it has created, and,
- Secondly, other teams verify selected alternatives on functions they interact with.

The set-based development strategy (Sobek, Ward, & Liker, 1999) does also take advantage from the reuse of precedents from records and utilises expertise as mechanisms of control for design reuse, through employing verification-feedback cycles to improve design attributes. Negotiation about several design alternatives takes place between subsystem teams, which progressively narrow their sets with increasing detail as the project progresses.

After the verification of product designs, the relevance of decisions consists of their effect in constraining the freedom of later project activities (Andreasen & Olesen, 1990) on the product design being developed, on the kind of approach to generate the details, and on the strategy involved. These include constraints on detailed design tasks such as the construction of prototypes and the design of manufacturing processes. As a result of engineering judgment made under limited knowledge, dispositions in product development often retain flawed predictions of later impacts from choices of design parameters (Flanagan, Eckert, & Clarkson, 2003). The role of design parameters in dispositional influences is very often missed, as activities during early design stages cannot grasp the issues they deal with.

Such issues reflect the performance of decision-making in engineering design, which involve social and cognitive processes characterized by circumstances in three classes of descriptions: attitudes, constraints and classification (Dwakaranath & Wallace, 1995). According to Dwakaranath and Wallace (1995), decision problems are framed according to the definition of prior criteria; these are refined through the decision process, which promotes the emergence of new factors understood as relevant to the decision problem.

These issues have significant implications for design teams making decisions:

- starting from available information, designers engage in branching out issues and alternatives in decision discussions;
- then criteria are updated along the emergence of situations, while previously considered factors may be forgotten during the decision process.

This branching out of phenomena works in such a way as to explore the network of factors that play out in the developing design against requirements as criteria, but there is always incomplete clarity regarding how the system and the application work; this creates a tendency to forget about prior criteria (design requirements, for instance) and to generate new ones through the decision process. This influences the mechanism through which set-based development works, which is heavily dependent upon feedback generated from the decision process. This feedback has two specific roles in developing a set-based design: evolving the internal design of modules by guidance to the search for intersections among subsystems; and developing the maturity of module and system designs by the management of the variety of alternatives to a more narrow range. Both uses of design feedback entail dealing with uncertainty in system-wide and component design configurations, which requires clear interface objects in the product design, with specific ranges of acceptable outcomes (Terwiesch, Loch, & De Meyer, 2002) to be verified and negotiated.

If the information needed is not available, development teams need to clarify structural and parametric relations in components and interfaces through an iterative approach. Such design cycles confirm the directive role of feedback for adjusting design characteristics against emerging properties that change the calibration of desired attributes. In this context, records that include the experience gained from testing and manufacturing establish guidelines for design work and preferred parameter ranges which alternatives must meet if they are to take advantage of current capabilities in design and manufacturing (Sobek, Ward, & Liker, 1999). This allows the adaptation and reuse of previous designs; by so doing, design teams act to diminish the uncertainty in novel developments; however, this may increase the ambiguity from conflicts in interfaces that are changed from a previous design to the new design (Eckert, Stacey, & Earl, 2005). Such problematic on ambiguity – and uncertainty – is also typical of design decisions and can be reflected upon under the concept of information inadequacy; this is due the lack of structural knowledge about (ambiguous) problems, or to the failure of current resources to secure knowledge about complex structures of interacting design issues.

Pich, Loch and De Meyer (2002) suggest comparing assumptions between influences of design issues to design activities and views held by designers about cause-effect relationships among the issues being considered; should this comparison indicate an inadequate level of information, two approaches are suggested for dealing with ambiguity and uncertainty: to learn about emerging factors and causal relationships; and, to select factors and relationships on current options to realize their outcome. The continuous verification of alternatives and parameter ranges in set-based design (Sobek, 1996) anticipates feedback and promotes the negotiation of design parameters in ranges as opposed to the remediation of discrepancies between values in the same parameters. This negotiation process is affected by factors that change the environment to which the product is originally intended (exogenous uncertainty), or by characteristics of the product design itself whose implications for design requirements designers cannot fully grasp (endogenous uncertainty) (Pich, Loch, & De Meyer, 2002).

In response to this problem, experimentation techniques work as a resource that elicits and gathers knowledge about the developing product regarding issues that are as yet unknown in general or issues that are specific to a particular project. The use of simulation and prototyping in product development is determined by the relationship between the cost in terms of resources and the benefit of learning how to make the developing design best suitable to requirements in the ongoing project. Expensive prototype-building, risk-sensitive designs and complex error correction processes influence the need for increased simulation and increased headcount to screen for design errors and reject bad designs (Thomke, 1998). More expensive test procedures and difficulties in matching test conditions to design requirements makes parallel testing less attractive. Integrated, tight-packed architectures are more likely to require sequential and iterative testing that increases and improves learning. However, parallel testing on different alternatives provides more options for choosing the best design (Loch, Terwiesch, & Thomke, 2001).

The problems of uncertainty and ambiguity are not only related to the product design and/or its application, but may also exist across different interpretations of design parameters or requirements. This issue contributes to the difficulty in assessing the impact of design characteristics in aspects such as product risks, for there is a lack of shared understanding of risks and uncertainties regarding the product and the process (McMahon & Busby, 2005). In the long run, the inability to grasp influences from design issues on downstream activities makes it difficult to enforce directives for design work, and allows unintended constraints to arise. A review of practice in conceptual design reveals that the more concrete a solution becomes in the eyes of designers, the greater will be the use of graphical models; more complex configurations will require greater use of block diagrams and system budgets to maintain a grasp of functions and design parameters (Bonnema & Van Houten, 2006). This helps to develop an overview of how design requirements translate into specifications of function and behaviour, to which methods such as functional modelling are used to decompose an overall function into chains of sub functions linked by energy, material and information flows (Pahl & Beitz, 1996).

Similar approaches involve the use of representations as determined by the levels of complexity and concreteness: block diagrams model partial components of complex system to ensure the coherence of design criteria (Harlou, 2006); and, component-based sketches (Hubka, Andreasen, & Eder, 1988) are preferred in representing working principles and system layouts. Illustrations in patent descriptions (Clausing & Frey, 2005) represent attributes of form and construction in an invention, whose utility is justified by functionality claims. When robustness is claimed for mechanical inventions (Jugulum & Frey, 2007), cutaway drawings and body diagrams are most frequently used to represent design attributes. Detailed models and working prototypes present richer descriptions of solution alternatives and of their physical behaviour, which motivates their extensive use (Ulrich & Eppinger, 2002). Geometry construction work in 3D CAD models can be translated to other representations of design concepts, a procedure which is known to shorten the time between building and testing (Baba & Nobeoka, 1998). Rapid prototyping from CAD models (Van de Velde, Van Dierdonck, & Clarysse, 2002) helps to clarify concepts by translating CAD files into physical models.

Information about design attributes is more expensive as it requires simulation experiments on detailed models (Thomke, 1998), due to the need to quantify design parameters. Hence, there remains a need for simpler models that can interpret quality attributes in concepts based upon existing knowledge. As models are expensive in resources, the occurrence of failure is linked to insufficient scrutiny of solution alternatives, and lack of awareness about the losses caused by past design mistakes (Petroski, 1994). This is reinforced by designers' lack of awareness of the knowledge available to them for assessing and managing design issues, which can only be mitigated by experience.

Such issue can be partially addressed by developments in engineering knowledge management, such as the classification of design knowledge. Taxonomies work by classifying different types of information, in order to develop indexing mechanisms that will facilitate the acquisition and retrieval of design information that is relevant to particular design issues (Ahmed, 2005). The derivation of ontologies and taxonomies can be carried out through empirical research; Ahmed (2005) extracted generic types of design information from data contained in design documentation, and from the expertise of designers and managers involved in projects. Another example of the use of empirical research on engineering knowledge consists in the interpretation and the development of design principles or heuristic guidelines (Ahmed & Wallace, 2004). Extracted from prior experience or from the observation of activities in the design process, both employ the translation of visual and behavioural signs extracted from models and tasks in the design process towards 'rules of thumb' and strategies to deal with design parameters to fulfil requirements.

One significant instantiation of this line of reasoning consists of the definition of design principles regarding relations between component dimensions and properties, extracted from long-term experience (French, 1992). This is applied with the suggestion of heuristics for the modularization of product architectures starting from functional system models (Stone, Wood, & Crawford, 2000), recognized from the interpretation of function structures. The other approach consists of observing the behaviour of practitioners while carrying out design tasks fot he assessment of different levels of expertise (Ahmed, Wallace, & Blessing, 2003) and the extraction of objective courses of action that lead to solutions, such as done with the aerospace industry (Ahmed & Wallace, 2004). Current developments provide basis for establishing prior definitions for the intended classification; this is complemented by the extraction of novel types from empirical data and their validation in dialogue with users (Ahmed, Kim, & Wallace, 2007).

Method

The present paper is part of an investigation intended to support the use of engineering knowledge for the assessment of design attributes during early design phases in product development. The study was motivated by this need, aiming to contribute with understanding on the inter-relation between product development strategy and engineering knowledge management. This is focused in the effects of the use of engineering knowledge on development strategy in innovative R&D projects. This study focused upon:

- first, a perspective on the evolution of solution alternatives that influence the effectiveness of the set-based approach; and,
- second, understanding of the conditions necessary for speeding up the convergence of set-based development practice towards a principle solution.

This research focuses the extraction of design issues from alternatives, regarding the way designers identify failure modes that must be eliminated through appropriate working principles. Current methods for robustness, reliability and safety were found as unfeasible for this practice as most of the input they need comes from detailed design information, which is unavailable during early design phases (Marini, Restrepo, & Ahmed, 2009; Marini, Restrepo, & Ahmed, 2010).

In response to this, we aimed to investigate the following processes in industry: how design flaws motivate the rejection of alternatives, and influence design feedback during concept development. This was investigated through a three-year case study about how design practice influences development strategies for problem-solving in solution alternatives. This study deals with a mechatronic, precision-mechanics medical device, the dose mechanism of an insulin injection pen, which is integrated with electronic components. Any shortcoming in its performance may generate life-threatening implications from the application of insulin in diabetic patients, leading to fluctuations on blood sugar concentration. This was performed as a longitudinal case (Yin, 1989) to investigate the use of design information to evaluate robustness, reliability and safety attributes and their implications to the course of action in concept development. By comparison with other studies about development strategies in the automotive sector (Sobek, Ward, & Liker, 1999), the insulin injection pen has the distinction of being a product subject to stringent regulatory requirements owing to the immediate implications for human life in the case of failure.

Within this context, the regulatory framework for medical devices compels accountability by demanding design reports on product risk throughout product development (ISO 14971, 2008). While medical devices may seem simple as regards the number of components – the pen device has around 20-30 components – their development requires thorough verification and validation. The relatively low number of components involved often leads to the belief that a project team with few engineers will suffice for the job. The core project team for concept development was composed of the project manager, three mechanical designers (two veterans), one risk specialist, and three electronics engineers (one of them was a veteran with more than 15 years of experience). However, in view of the degree of integration and complexity of the newly developing device, the project team had requested increased manpower throughout the project.

The case study involved collaborating with the manufacturer of the medical device in order to analyse the concept design information generated over a three years period during the product development project of the dose mechanism and the measurement system of the insulin injection pen. The approach consisted of collecting retrospective data on 36 months of concept development activity for developing the principle solution for the new design, along with interviews that explore the context and validate the findings on the information about the project, see Table 1. As the aim of this study was to investigate, by means of a case study, current design practice to better understand the interface between design methods and product development strategies in early design phases, it can be understood as a first descriptive study within the design research methodology (Blessing & Chakrabarti, 2007).

Four data collection approaches, were used:

- document analyses;
- reverse engineering;
- interviews, and,
- models of solution alternatives.

Document analyses, reverse engineering, and modelling and representation are situated in relationship to interviews, in which source data from the collection methods was cross-validated with the statements of designers.

Table 1 - Case study on insulin injection pen (Marini, Ahmed-Kristensen, & Restrepo, 2011)

Characteristic	**Doc. Analyses**	**Rev.engineering**	**Interviews**	**Model/represent**
Case executed with actual project	17 partial/closure stage presentations	4 sketch sessions of work principles	5x open-ended on technical issues	9 function modules in all alternatives
Researcher observes project	5 technical risk stage reviews	20 alternatives of solution (concepts)	3 mechanical engineers, 1 system engineer and project manager	Several overview and close-up screenshots of alternatives
Longitudinal and retrospective study	14 feasibility reports on features	50 CAD variants with small changes	Not mediated, with video records. (45min each)	3 sequence/timeline development graphs
Comprehensive study of situation	4 matrices about set-based dev.	9 modules in system formulation	3x semi-structured on concept selection decisions	Total of 50 failure occurrences to reject
36 months from sketch to solution	Several reports from evaluations	61 work principles in all alternatives	Mechanical engineers: 2 veteran, 1 expert; Risk specialist	Total of 47 mentions to technical risks
Lead time launch in 6 to 8 years	Validated by interviews	Associated to interviews	Specialist as mediator, with video records (60 min each)	Developed upon interviews

The table includes general descriptions about the involvement of the researcher and the conditions in the study. Document analyses were carried out to raise evidence from project documentation along with the relevant information about solution alternatives and design activities. After this, a reverse engineering approach (Otto & Wood, 1998) was used to collect design characteristics of solution alternatives that were relevant for the findings. Interviews (open-ended and semi-structured) were carried out to explore the facts of the design activity in the project, such as the designers involved and their roles in the project, the use of media to record information, and the motivations driving the development of solution alternatives. Modelling and representation activities were carried out to illustrate the findings of the study.

The work was retrospective to the ongoing product development process, as the activities of concept development were already concluded by the start of the case but few issues of conceptual design were still under consideration for change. Document analyses were carried out throughout the whole case, in order to understand when solution alternatives were generated, which issues took place, and how the principle solution was developed. Reverse engineering was used to identify the functions performed by design alternatives, their working principles and any similarity between these. Open-ended interviews were carried out with all the mechanical designers, one system engineer and the project manager. Semi-structured interviews were carried out with mechanical designers only. Questions put to interviewees focused on two types of issues: challenges and measures to manage technical risk (open-ended), and the rationale for selecting and rejecting design alternatives (semi-structured); these questions helped guide the search for information in document analyses, and validate the findings from documentation and reverse engineering (Marini, Ahmed-Kristensen, & Restrepo, 2011; Marini & Ahmed-Kristensen, 2012).

Results

The data collected during the study was analyzed with a view to understanding the general approach to concept development, the solution alternatives and their working principles. The relationships between the alternatives and the reasons for their rejection were examined in the data; these reveal the interface between the design methods and product development strategies, which was revealed by characteristics of the early design of the insulin injection pen:

- *The characterization of working principles and embodiments of solution alternatives* for the dosing mechanism – and associated measuring system – of the mechatronic insulin pen provided a perspective for the interaction between the design methods and the product development strategy. This entails a description of design examples from the project, in order to explore and consolidate criteria to define the effectiveness of the actual development process in the use of design methods and in its performance in accordance with the intended development strategy. Engineers revealed the strategic difficulties in the point of view of the design team through the study, and the courses of action they employed to deal with these. The configuration of the results from the design work hinted to characteristics of product design that generated uncertainty and ambiguity.
- *The relation between design reuse and failure modes in the verification of alternatives* made the interface between the activities of the design team and the outcome from the application of verification methods. The description of the similarities between the different alternatives, reflecting design reuse and the construction of variants to working principles, represents the activities of the design team. The study obtained knowledge about the reasons for the rejection of solution alternatives by interviewing engineering designers, who revealed the strategic choices regarding the design of alternatives and the courses of action they chose to perform, as seen through their experience. The issues revealed by designers indicated what they needed to do and the choices they faced in developing the principle solution towards the product.

- *The relation between design decisions and feedback to proceed with the project* developing the required product attributes was found to make the interface between decisions taken by the design team and further development of the solution alternatives. The assessment of failure modes in alternatives allowed interpreting the design phases and verifying the failure modes related to working principles in solution alternatives. The study collected information about the decision points in the project and inquired designers about the considerations they made in regard to attributes of robustness, reliability and safety in solution alternatives. These considerations were tracked against records in the project database mentioning the decision points and the issues in need of solution.
- *The overview on the alternatives designed and the methods used through the timeline* represents the development process regarding the concreteness of design models, the development milestones; the use of verification methods, and the parallelism between solution alternatives. A description of the concept development process was established, representing the path of activities executed by engineers up to the final choice of the principle solution for the internal mechanism of the insulin injection pen. The resulting overview allowed the assessment of how design methods and development strategies interacted through the development of solution alternatives to a candidate design. Prior to presenting the results, the insulin pen needs to be described in both general principle and functionality levels, as shown in Figure 1.

The principle of the insulin pen is based upon the displacement of a cursor that controls the piston moving within a rigid body, which is responsible for injecting the dose of medicine into the patient in a way similar to that of a normal syringe. Based on this interface between the cursor and the piston rod, the injection principle works with two separate states: dose set-up and dose output. These states determine how the device is supposed to work, and aspects of its configuration. The displacement of the cursor is controlled by a dial button and indexed in individual units. This positioning of the cursor in relation to the dose-set mark must be accurate as it determines the amount of medicine to be delivered. By pressing an activating rod, the piston is engaged or unlocked and then moves, pushed by a spring with accumulated energy from backwards displacement caused by the movement of setting the dose or by the volume occupied by the medicine against the piston (not shown in the figure for the sake of simplicity).

In order to identify the design characteristics that led to the rejection of solution alternatives, each design was reverse-engineered to working principles satisfying individual functions. Table 2 shows the variety of working principles for the ‘actuate displacement’ function, which is responsible for causing the piston to move and thus deliver the medicine. Working principles for this function implement the following activation modes: force acting on the cursor activates the piston; and the cursor releases the piston being pushed by force. In the mechanism, this force is carried either by human energy or by a built-in spring; alternatives with the built-in spring were better adapted to precision positioning of the cursor-piston pair in regard to the dosage level. Hence, the majority of alternatives use this approach to performing the function of activating the displacement of the piston.

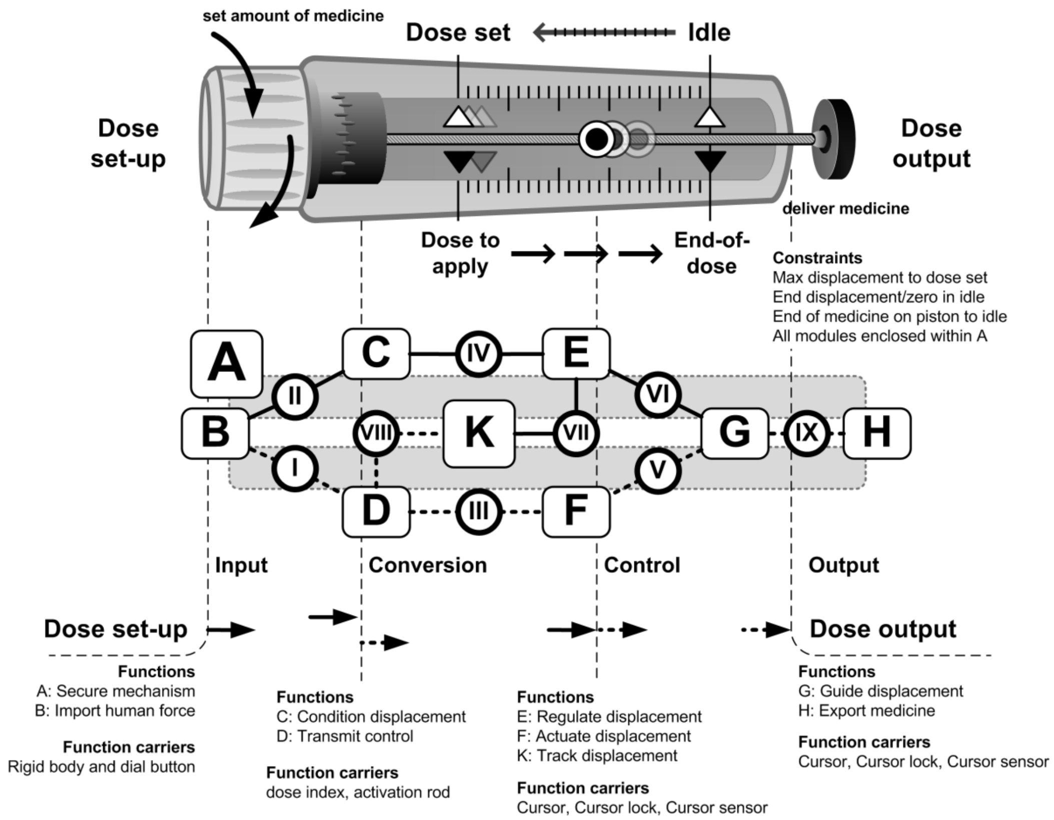
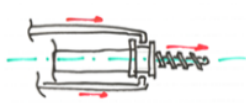
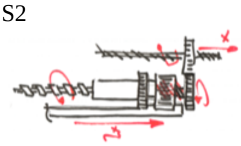
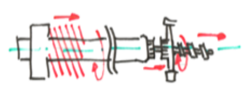
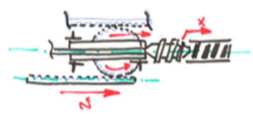
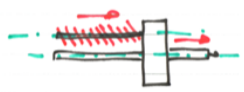
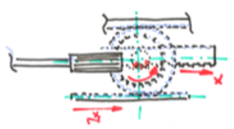


Figure 1 – Generic working principle of the insulin pen

Design complexity from the variety of working principles in solution alternatives is at three levels:

- Working principles with component combinations that yield different modes of action;
- Womponents responsible for performing a single function in the device system; and,
- Components that perform two or more functions with different functional surfaces.

Table 2 - Variety of working principles for a single function of the insulin pen

Function	Alternatives / Working principles		
Actuate displacement	CC1 	S2 	A31 
	CC2 	S3 	O1 
	S1 	A2 	O3 

Uncertainty does escalate from the combination of these kinds of complexity and is aggravated by the ambiguity from novel designs for most components of the pen. The working principles CC1, S1, S2 and S3 shown in Table 2 were designed for activation by human force; this is done through a physical link between the component receiving force from the human body and the component responsible for pushing the cursor and, in consequence, the piston. CC2, A2, A31 and O1 were designed for activation with energy mechanically stored by a spring within the device; activation was achieved by movement between the human body and the cursor that either engages or releases the piston. The motion of the piston when delivering the dose needed to be steady and accurate, in order to deliver a progressive amount of medicine at the intended quantity. Table 3 shows statements obtained from the designers during interviews, about the failure modes that occurred in the project; these were made in response to the question of why solution alternatives were rejected, a question which the designers answered in terms of mechanical behaviour satisfying functional requirements influenced by user behaviour.

Taking into consideration that either the cursor or the piston are pushed, and friction or meshing are essential behaviours for controllable injection, failures can have catastrophic implications to functional requirements, Failure to activate the piston may cause the delivery of more or much less medicine than intended, or provoke injury due to unintended mechanical behaviour; failures where there is lack of control over the piston may cause an overdose of medicine, an underdose of medicine. Malfunctions of the device were then coded through the study to facilitate the analysis. slip and run-off occurs when the piston escapes the control of the cursor; stroke-out takes place when an input displacement falls outside an intended movement range; setting + dosing takes place when the interface between the cursor and the piston becomes indeterminate; a jerky/jammed state consists of intermittent interlocking which inhibits the delivery of medicine and causes hazardous disturbances in the interface between the device and the patient; and lack of friction connotes an indeterminate interface between cursor and piston, which creates risk of underdosing..

Table 3 - Failure modes for the rejection of alternatives, milestones and issues stated by designers

Failure	Example	Issue
Slip & run-off	Issue M1: "Dosing control after injection"	Interview: "You must be sure the piston rod should be staying there; there was a little chance for it to slip a little, we were sure."
Stroke out	Issue M2-1: "Dose setting below zero"	Interview: "Where is the turning point, where does it rotate, where is the zero… is it here… we were moving around this point actually."
Setting + dosing	Issue M2-1: "Necessary tight tolerances"	Interview: "The user can't dial and also set the dose; quite difficult to make sure you've changed the state when you release this [lock]."
Jerky / jammed	Issue M1: "Several moving parts make it jam"	Interview: "Get rid of locking and gaps in the system; yes, you also have high pressure on some of the parts … could be a problem."
Lack of friction	Issue FEA3: "It moves after dosing"	Interview: "The quality of the lock… up to fifty times it was sharp; You'd be always worried about this lock… would it be able to slide?"

Table 3 classifies issue statements found through the project as follows: the first column displays the coded name for each issue; the second column displays how the issue was mentioned in the document mentioning the reason to reject given alternatives; and, the third column displays how designers described the issue when asked. A closer look at the statements reveals the association of clear descriptions of purpose with expressions of uncertainty on whether alternatives would satisfy functional requirements. This uncertainty is more specifically linked to whether mechanical components would perform to their intended purposes; moreover, ambiguity is expressed in terms of the lack of clarity in documented statements about specific locations or components that were moving in particular manner so as to cause the issues that designers pointed out. Designers may also have left such information unstated and implicit, which takes for granted that interlocutors have prior experience of such characteristics.

A number of 20 solution alternatives was generated during the three-year period of concept development which was analysed through the case study. Figure 2 shows the variety of working principles used and reused in the solution alternatives, mapped together with the reasons found for their rejection. The developed alternatives are shown in the horizontal axis (S1, S2, S3, etc.), with the coded reasons for rejection and the variety of working principles placed the vertical axis. The occurrence of failures that motivated rejection, and the reuse of working principles, are represented by arrows; repeated occurrences of failure motivating the rejection of alternatives are highlighted in red. The variety of working principles in adjacent functional units was found to be highest in proportion to the complexity of function units as measured by their number of physical interfaces.

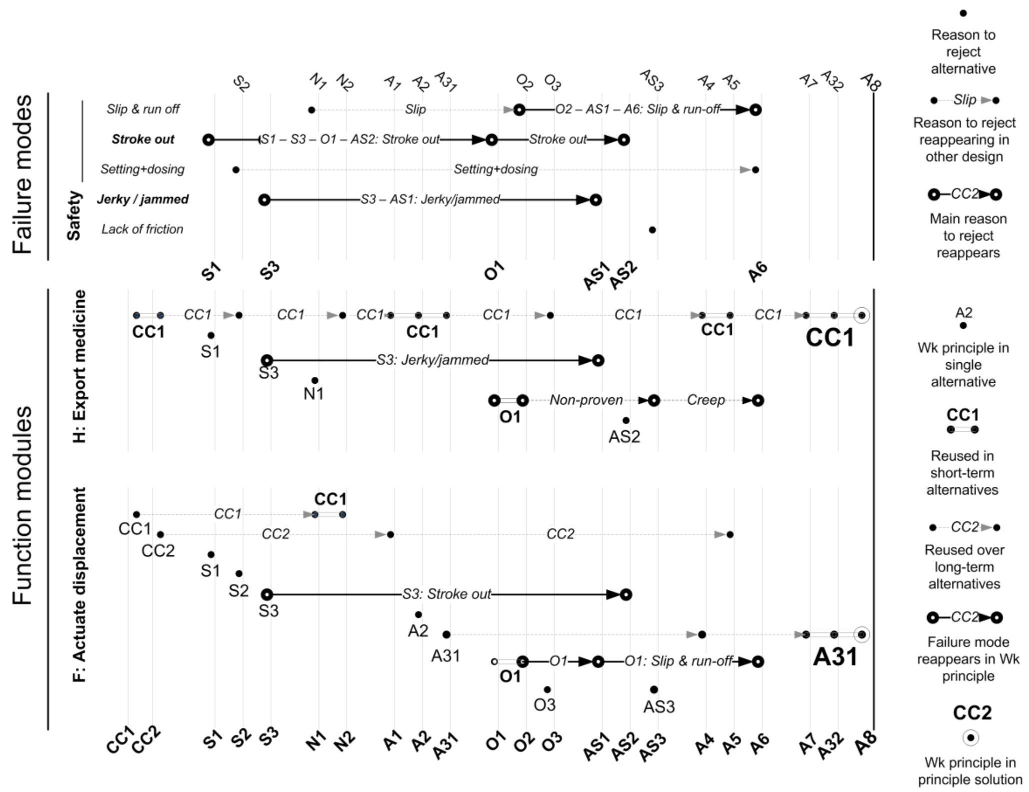


Figure 2 – Correspondence between failure modes and design reuse – safety failures

The example illustrated displays the occurrences of rejection linked to failure modes against safety requirements. The Actuate displacement function was found to have an average of eight interfaces through solution alternatives, and the export medicine unit was found to have an average of three interfaces. In this regard, the variety of working principles increases with the number of physical interfaces, as there are more degrees of freedom between components carrying a single function, which designers need to be negotiate before they achieve a design that provides satisfactory performance against requirements. Another observation found through the study was the reappearance of reasons for rejection in parallel with the reuse of working principles from alternatives that were previously rejected for the same reasons: alternatives S3 and AS1 employed the same working principle, and were rejected for the same reason – a stroke-out failure.

This was found to take place more often on function units that were more complex. For instance, the actuate displacement function, whose working principles are described in Table 2, has the following characteristics that increase complexity in addition to the novel character of their configuration in comparison with current designs: first, the components involved perform more than one function – some also work to displace the cursor while the piston is fixed when setting up a dose, but with different functional surfaces; second, at least four components are involved in the function of actuating the displacement by the piston –the number of interfaces was counted to be higher than that by at least a factor of two.

While several specialties were involved besides product design– such as risk management, manufacturing engineering electrical and software engineering – from the beginning of concept development, the variety of principles developed by designers prevented the development of standard interfaces. There was uncertainty about how to transfer movement to achieve the intended mechanical behaviour, and consequently the expected use behaviour, due to the fact that decision statements described the failure modes motivating rejection of alternatives, yet could not pinpoint the failures that took place or identify the issue so as to provide feedback to further alternatives. The reuse of working principles that had failed previously ended up expending development resources that otherwise could be invested in implementing novel solutions from principles that worked well and needed improvement.

The characteristics being developed in solution alternatives enabled the division of the whole concept development process into the phases prescribed in literature (Ulrich & Eppinger, 2002). The first phase, concept development, concerns the implementation of working principles and their integration into alternative mechanism formulations. These provide approximate descriptions of working principles and of their physical implementation in product architectures. While design engineers made significant use of CAD and physical prototypes in the process, the development of solutions with different working principles that employ similar geometric features has complicated the ability to locate sensitive points that are more likely to lack functionality or fail during their performance. This has implications for the use of design methods for verifying solution alternatives in early design stages, as these depend significantly on the ability of designers to identify problems, point out their locations, and predict the manner in which these will escalate through system components, thus permitting one to grasp their criticality.

The effect of decisions on the feedback to new solution alternatives, and by consequence to the development strategy, is displayed in Figure 3. This shows the development timeline highlighting the relationship between the rejection decisions and the generation of new alternatives. The decision-making milestones are shown in blue, while the generation of new alternatives is shown in red. The decision–feedback loops are shown in red dashed squares, and identified from A to G. The first phase shows several parallel alternatives on the run, with three feedback loops (A, B and C), which is the same number of feedback loops as in all subsequent phases. The interface between decisions taken by the design team and further courses of action is displayed by the identification of key design decisions and their relationship with the development of new solution alternatives. These decision-feedback loops show three different patterns: first, a feedback loop with several alternatives and fewer inputs than outputs; second, a feedback loop with several alternatives and fewer outputs that inputs; third, feedback loops with two-to-one or one-to-one correspondence between inputs and outputs.

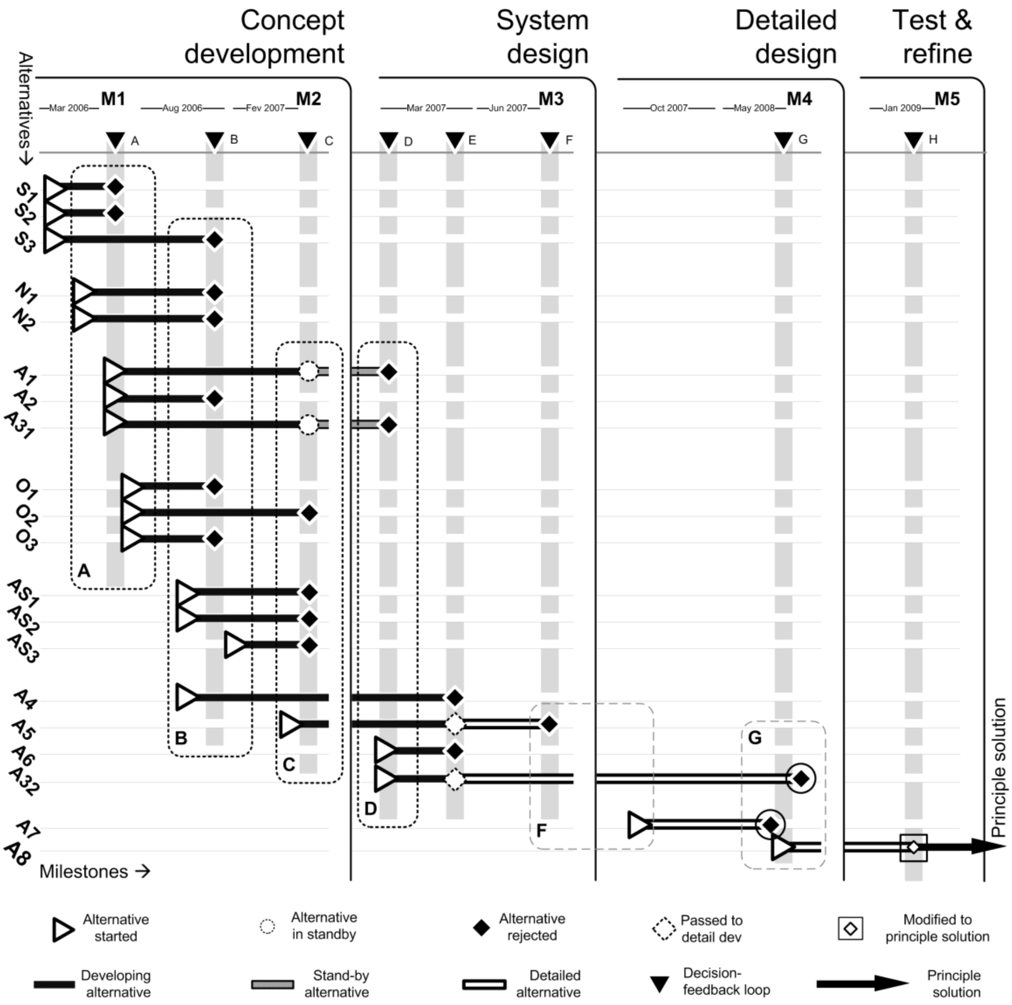


Figure 3 – Timeline of alternatives developed, evaluation milestones and knowledge reuse

The first feedback loop marks a divergent phase in concept development, where more solution alternatives are developed in response to issues manifested in prior work and supported by the knowledge thereby acquired. The second feedback in turn inverts the pattern which shows more alternatives being rejected against fewer ones proceeding. In this regard, the number of decision statements is far higher than the number of feedback statements. Nevertheless, the correspondence between decision and feedback statements is significant, and statements from designers can be divided into those regarding decisions and those regarding risks identified as feedback from decision-making. This confirms the role of decisions as defined in set-based development, as influencing the convergence of alternative designs into a preferred solution. The development of alternatives was shown to continue through system and detailed design, which indicates the negotiation of interfaces between system functions. This reflects the adoption of a set-based approach, where solutions are explored and refined over a long period. Designers continuously negotiate design interfaces until they reach agreeable strategies and converging values for establishing the solution principle. Later alternatives are developed in increasing detail, reusing working principles used in previous alternatives. If some of them are rejected, new alternatives are designed with variations in architecture and changes in working principle.

Following this pattern, the reappearance of failures shown in Figure 2 took place due to the neglect of issues from prior alternatives by designers through several milestones during the concept development process. This fact was observed for a single decision, where designers tended to forget and dismiss prior criteria through single decisions (Dwakaranath & Wallace, 1995), and was recurred through the project timeline as decisions and feedback statements correspond to each other, but motivations for rejection tended to reappear throughout the project. Examples can be drawn from the statements about tolerances and friction, as shown in Table 4.

Table 4 - Decision and feedback statements from concept development of insulin pen

Phase	**Decision**	**Feedback**		
	Reason to reject	**Types**	**Example**	**Record**
M2-1 **Aug 2006**	Interview: “Very good tolerances when you stack them; you bend and you don’t know how much it’s going to return”	Tolerances	Interview: “You have the movement of electronic (…) you should be sure this [components] will be able to follow each other.	Gap in linear components Dripping
	Interview: “Very small parts to be machined, and high friction because there’s a lot of interfaces between components”	Friction	Interview: “The piston rod in this system was… not easy to retract There's a lot of interfaces, and the complexity, I think so.”	Solve friction conditions
	Interview: “We needed to be sure whether it could deliver individual increments but there was a chance it would slip a little”	Sensor interface	Interview: “If you want to mix mechanical and electronic concepts, you must be aware that you haven't got so much gap.”	Prepare for electronics Improve clicks

The statements on tolerance can be traced to different issues: the spring effect in slender components working as pistons, and the accuracy to which components guided each other through the mechanism; these issues were linked to the same the effect and purpose of positioning the cursor/piston interface within the device. Another statement of this type related to friction, but here both statements covered the same issue.

The way the friction problem shifted location as displayed in Table 4 was not revealed in either of the documents referring to decisions and feedback: instead of taking place in several interfaces which are seen as ambiguous, the friction becomes concentrated in the cursor/piston interface. The behaviour in this principle allowed dose set-up and dose delivery, but made it difficult to create enough free space with the piston for the empty storage unit to be replaced by a new one. Experienced designers are able to grasp the way design issues are supposed to evolve by adapting their experience to the new situation and being able to predict how component interfaces will progressively be solved (Ahmed, Wallace, & Blessing, 2003). This negotiation of interfaces between system modules carrying individual functions and between components within modules is one of the basic tenets of set-based development. However, when solution alternatives present a variety of working principles, this negotiation process becomes complicated, due to several possible pathways to solution that did not fit prior experience.

The study has shown that knowledge acquired by using design methods to evaluate and verify solution alternatives influenced decisions and feedback on solution alternatives. In this context, the development of solution alternatives focused upon issues regarding the performance of mechanism designs in order minimally to satisfy design requirements. Figure 4 confirms the strong relationship between the use of verification methods and decision-making-feedback through project milestones, as it shows the use of methods was preferred just prior to making decisions. Changes in working principles reflect an exploration of possibilities in regard to satisfying the requirements of given system functions. As a result, 8 evaluations are performed on 14 alternatives, while the other 6 were evaluated with 12 instances. This highlights the difficulty in verifying solution alternatives during early design stages. The amount of information being handled by the designers was seen to have a major influence on this issue. In this context, the reuse of past designs facilitates much of the design work, as these incorporate knowledge which is already developed (Eckert, Stacey, & Earl, 2005); however, it becomes a problem when different solution alternatives fail due to the same problem.

The reappearance of failures as displayed in Figure 2 indicates that insufficient knowledge was collected from previous decisions, as they were taken without clear enough information on the motivations for failure of solution alternatives through the development process. This problem was seen to take place due to two issues: the variety of solution alternatives being developed through the design process, and the degree of detail to which methods characterize product design. At the same time as the available information enables designers to make decisions, failures reappear due to the lack of implementation of previous feedback into further development. Considering the strong link between decisions and design feedback shown in Figure 3, the results shown indicate shortcomings on the learning mechanism about failure, from the first occurrence through decision-making and feedback loops – data collected from the study shown that reappearing failures were only conclusively corrected upon their second or third occurrence across several alternatives. The lack of ability to pinpoint the locations and mechanisms of failure in the working principles was seen to be derived from the ambiguity in the product architectures of solution alternatives, with influence on the parameters effectively working in the selected principles and in their relationship to overall design parameters that were judged. Here complexity in individual combinations of working principles was escalated to complexity across several different combinations of principles with individual sets of local design parameters.

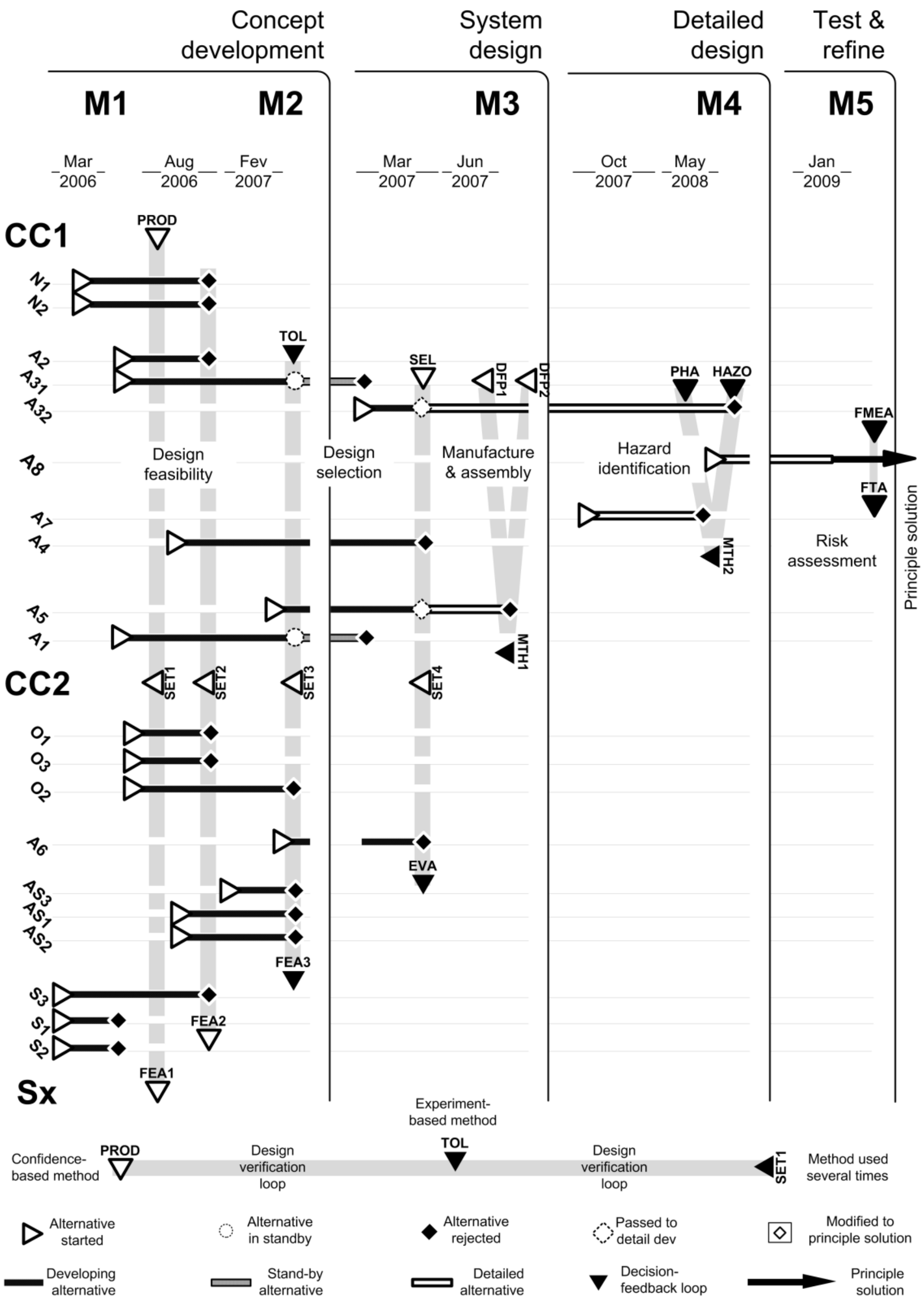


Figure 4 – Evaluation methods and convergence of alternatives towards the solution principle

Table 5 – Comparison of queries in design methods: SETx table and EVA pre-selection report

SETx table	**Definition, example**	**EVA report**	**Definition, example**
Favourites	Favourited by individual designer “AS2 – Kenny”	Alternative development	Solution alternative being evaluated, and models available. Report: Alternative A5:“Flat torsion spring (...) Assembly status in CAD (...)”
Functional model	Is there a mode for testing? (Yes/No) “S3 - Yes”	Critical subfunctions	Critical elements for functionality and suitability to requirements Report: “Spring almost impossible to calculate, prototypes and test will be the right way to start dimensioning.”
Accuracy / force test	Is there a test on function? (Yes/No) “A1 - Yes”	Dose button / dose set-up / mode change	About the user commands, dose set-up state and mode change. Summary: “Range: 0 to max in 1 IU steps, possible dial up and down”
Sensor type	Type of sensor measurement is rotary or linear? (nR/nL) “AS1 – nL”	Dosing / End-of-content	About dose output from cursor/piston mechanism and its range limits Summary: “The preloaded torsion spring drives the mechanism”
Torque/force	Torque for dose set-up [Nmm] or force of dose output [N] “A1 – nn Nmm”	Dosing / End-of-content	About dose output from cursor/piston mechanism and its range limits Detail: “Specifications taken from CC2; mean flow with inner diameter section of nn mm2: xx IU/sec.”
Set below zero	Score for avoiding dose set-up in reverse from zero location (1 to 5) “A1 – 5”	Dose button / dose set-up / mode change	About the user commands, dose set-up state and mode change. Detail: “Set above max stopped by rotary interface in thread, moving axially towards the rotary stop surface”
Possibility of ½ IU / U200	Is it possible to double the increments? (Y/N) “A31 – Yes”	½ IU / Blood in medicine	Ability to shorten increments/ avoid suction of blood to mix with medicine Report: “At end-of-dose the system is spring loaded forward, so there is no play allowing the piston to move.”
Accuracy reading	Score for accuracy of sensor reading (1 to 5) “AS1 – 2”	Accuracy / sensor	Response to changes of state and measurement Report: “The position of the piston depends on the rotational position of the ratchet and the precise locking between the base part and the ratchet.”
Reliability	Score for overall reliability in use situations (1 to 5) “A31 – 3”	Drop test / sealing	Resistance to elements and environment Report: “It is believed to be able to withstand at least the same or higher drop specifications than current pens

The verification of solution alternatives through concept development was carried out with the use of evaluation methods informing designers whether alternatives can suit design requirements, and giving designers the bases for moving forward with the project. Regarding this context, Table 5 compares sample queries of two methods used during the concept development of the insulin pen. The SETx method stands for the matrix used to compare attributes of alternatives as from set-based development, adapted to the scope of developing an insulin pen. EVA stands for the evaluation carried out prior to using the Pugh matrix in order to choose alternatives for system and detailed design. The SETx method uses a spreadsheet format with individual values, yes/no answers and qualitative scores, which is better for indicating confidence regarding whether alternatives will develop to satisfy design requirements. However, a decision was needed about which alternatives would be developed to system and detailed design prior to deciding the principle solution. For this decision to be made, effective concept verification was needed – not to signal a direction, but to make an actual choice regarding the alternatives to undergo system and detailed design. EVA was carried out prior to choosing the alternatives to follow through system and detailed design, reflecting the available level of functionality in the ongoing alternatives. Ongoing solution alternatives were directly verified against functional requirements with regard to key parameters and performance figures obtained from simulations and tests of early prototypes: alternatives manifesting issues which were unsolvable in the near term were discarded; alternatives whose mechanical behaviour was mostly satisfactory were maintained.

The generation of design information about individual alternatives, it is worth noting, required many months of resources and manpower, due to the innovative working principles being used: this meant there was no information about the use phase of the product –as being developed – was available and then prototypes were needed to support the verification of individual designs. In any occasion when making decisions, the designers' perceived confidence in distinguishing good alternatives from the others at a certain level of detail – fulfilling the requirement of the development model within the company – influenced the occasions when decision-making was performed. Such detail was seen to be associated with the presence of a consolidate design model that represented and/or carried actual functions of the product and communicated design properties to an extent that either allowed assessing the confidence on the feasibility of alternatives, or that allowed the verification of product properties (e. g., dosing force) against design requirements.

When uncertainty was seen as too high by the design team, only the confidence assessment was possible for the verification and judgment among alternatives, which indicated that future alternatives followed a trend of improvements based on the pool of expertise that was available among designers. Sketches, mathematic and CAD models which carried product properties to intermediate levels of detail – component layout, general dimensions – did not offer by themselves the degree of information needed to verify how alternatives performed. The confidence-based assessment, as made by designers with SETx, indicated a direction to further activities in concept development: alternatives showing poor functional performance were discarded at this stage, as they would either not evolve without increasing product cost or their mechanical behaviour was not fit to the purpose set for the product; alternatives which were good enough in overall performance and were deemed as having reasonable product costs were kept running.

When there was enough information to verify how the product design worked against design requirements, the few alternatives that performed in a satisfactory manner were selected, also in the condition that their resource needs for further development matched those available in the development project. Detailed CAD simulations and mathematical models carried detailed product properties that allowed the direct comparison of performance figures against design requirements. With such models available, ongoing solution alternatives were verified using the EVA method against functional requirements, with regard to key parameters and performance figures obtained from simulations and tests of early prototypes: alternatives manifesting functional issues with design parameters which were unsolvable in the near term were discarded; alternatives whose overall mechanical behaviour was mostly satisfactory were maintained.

The use of design methods, to a major extent, depends upon the information that is needed and on the available level of detail provided by models that represent and/or carry properties of developing designs to fulfil such information requirements. At the confidence assessment level, past designs were used as references for new working principles and for estimating fitness to purpose in developing solution alternatives. However, the choice of past designs as references was made ad-hoc through the design process, and this choice inevitably reflects the experience of the designers who participate in the project team; there was no actual method for improving the use of knowledge in order to increase awareness about the implications of selected product properties. This has had significant effect upon the implementation of the development strategy that was foreseen in principle, as the degree of certainty to which a new design was to be verified was found to depend on the amount of learning that has been cumulatively collected – throughout past projects and that ongoing – about how to achieve intended performance in solution alternatives. There was a clear link between availability of information, generation of knowledge and decision-making - a link which is now to be discussed.

Discussion

The results presented in the previous section demonstrate the ways decision-making, the choice of development strategy and design verification interact in a real development project. Firstly, the reappearance of failure modes through the reuse of working principles in different solution alternatives showed the intuitive use of ‘chunks’ from past designs to construct characteristics of the intended product for which there was a solution sufficiently close to satisfying design requirements within the ongoing design process (Eckert, Stacey, & Earl, 2005). Several relationships were observed as causes of the ambiguity when verifying designs that did not appear as similar in architecture but used similar principles, these were: a lack of clarity about which characteristics were carried over with the past design; and a lack of explicit criteria for constraints in the past design that affected its suitability to the new architecture. For example, the problem with the ‘export medicine’ function carried by the piston, which was carried over from alternative S3 to alternative AS1, occurred because that particular working principle for the piston did not make a stable interface with the cursor. This was later seen to cause problems with regard to its reliability and accuracy in use whose solution was unfeasible – a situation which reflects the delayed solution of known problems in the mechanism design. The issue of explicit constraints was demonstrated by the reappearance of the ‘stroke out’ failure, which reflected problems in S3 and AS2 with regard to controlling the range of movement of the cursor. The constraints of the new mechanism were as yet unknown as it was still under development; yet the constraints and limits of currently available designs could be assessed.

In regard to understanding product characteristics, structuring the product in several layers is seen to support the development of intended quality (Mørup, 1993). Design practice throughout the project under study showed a highly structured process, in terms of its having clear development goals and intermediate steps where solutions were evaluated in regard to them. Within this context, design requirements were structured around design and use characteristics (features) that were transparent to the people involved in improving the product. Decisions on solution alternatives were clear about the reasons why solution alternatives were discarded. However, the structure around features failed to provide the needed clarity about how these causes were taking place; the application of structures to the product design and the development process alone did not guarantee the solution of decision-making issues, as priorities were shown to change in the course of the design process and prior issues of concern tended to be forgotten or neglected through proceeding with the design activity (Dwakaranath & Wallace, 1995). In the original formulation of set-based development, the developing design is divided into subsystems, for which several alternatives are to be developed and implemented. The similarity in the treatment of criteria between individual decisions and several project milestones has affected the way set-based development was implemented through the project, as one of its key characteristics is the negotiation of interfaces in principles and ranges across alternatives for adjacent subsystems (Sobek, Ward, & Liker, 1999). The criteria in use have affected the functional scopes of individual parts and their variation across solution alternatives, with influences on the variety of interfaces being developed, and on the degree of ambiguity in the verification of parametric relations across solution alternatives.

Set-based development depends on a product being decomposed from systems with a relatively fixed scope of components and functions connected by common interfaces whose parameters will be negotiated (Terwiesch, Loch, & De Meyer, 2002); this reflects the requirement of a product structure whose subunits do not significantly change in scope and whose interfaces can be more or less predicted, regardless of the working principles being adopted. Product features involved distinct scopes of components across alternatives, and this has not supported the predictability or the standardization of interfaces between system functions. Components also worked as references to functions for structuring the product, in two different ways: either as performing embodiments with their respective features or as functional properties with their respective parameters. These issues caused ambiguity in the identification of the origin and mechanism of failure modes, and in the clarification of the constraints involved in the reuse of individual working principles, without significant support from product structures.

This reduced the effectiveness of front-loading, which as a strategy (Thomke & Fujimoto, 2000) for innovative products works to increase the level of confidence in the estimation and verification of the best feasible alternatives. In this context, the front-loading of information about prior projects into the ongoing concept development did not guarantee improved lead time, as problems with the reappearance of failures in solution alternatives reflected the lack of clarity with regard to the changes in scope and in the constraints involved in the reuse of past designs. Front-loading and preliminary information exchanges (Terwiesch, Loch, & De Meyer, 2002) illustrate the choice of strategies based upon the degree of ambiguity in the development of a new product design, and the findings from this case study shown the need for a change of emphasis, from starting upon prior analysis of the planned product to tackling ambiguity across working principles and parametric relationships. Concept development as observed in the study was surrounded by uncertainty and ambiguity, because understanding of the intended solution was at best approximate and incomplete. Hence, ambiguity could be eliminated under varied solution alternatives with different principles but it can be mitigated to improve the development of convergence towards the principle solution.

In the study, this convergence has slowly developed from several alternatives towards a set of options whose scope of characteristics and issues manifested a level of uncertainty that design teams could deal with feasibly. Considering the issues found across the analyses, the conditions needed to speed up convergence relate to the mitigation of the reappearance of failure modes that prevent alternatives from suiting design requirements. This is a natural development in the design process and has indeed been manifested in the more detailed stages, as displayed in the development timeline. Nevertheless, the results hereby presented shown the choice of suitable alternatives and the adaptation of prior solutions as feedback for improvement can develop at an improved pace of convergence into the principle solution. The clarification and explication of issues between decisions and feedback to further development should work to enhance the mechanism of learning from failure, which is an essential part of product design and development, as it has been observed to be a driver of successful innovation (Petroski, 1994; Petroski, 2001). The correction of design flaws was dependent on the involvement of designers, and on evidence from warranty claims and/or testing; mechatronic (integration) problems are more often successfully corrected; and flawed original designs are more often successfully corrected than adaptive ones. Effective cross-project communication and knowledge management should also guide designers towards better solutions (Gries, Gericke, & Blessing, 2005; Gries, 2007).

Two types of verification-decision-feedback loops were observed through this study: those based on actual verification of design requirements in key characteristics of product models and/or prototypes with product characteristics that were tested against models of the use environment (Thomke, 1998; Maropoulos & Ceglarek, 2010); and those based on degrees of confidence under moderate ambiguity undertaken under orientation of expertise that was elicited by opportunities from documentation of from daily life (Visser, 1995; Wallace, Ahmed, & Bracewell, 2005). In actual product verification, there is consolidated knowledge about the influence of increased use of simulations. They were found as effective in speeding up problem-solving cycles and opening up new possibilities of reproducing use conditions, by the ever-increasing capacity of computing tools to provide essential information to learning about product performance (Thomke, 1998)*. Digital mock-ups built virtually in 3D CAD files (Baba & Nobeoka, 1998), and physically by means of rapid prototyping and machining, (Van de Velde, Van Dierdonck, & Clarysse, 2002) facilitate access to information previously too expensive by building real prototypes for testing.

When considering degrees of confidence against ambiguous and uncertain design information in early design phases, the way forward consists in the generation of knowledge and heuristics that reproduce the actual expertise developed by designers over years of practice. One approach to heuristics is to observe expert behaviour and recognize strategies that can improve communication among designers (Ahmed & Wallace, 2004), through developing guidance frameworks that orient novice designers in eliciting knowledge needed to solve design issues. A fuzzier use of heuristics takes place when considering solution alternatives that are good examples of positive influence on the generation of better designs (Fu, Cagan, & Kotovsky, 2010). This mechanism was observed to take place during the study, solution alternatives whose evaluation was better at the start of the project played the role of originators to the final design.

In our view, knowledge management solutions have already been successfully applied to engineering design in order to support the leveraging of intellectual capital inside manufacturing organizations. However, problems such as deficient scrutiny of solution alternatives, attitudes that preclude failure prediction, and the lack of methodologies for building a common understanding of the risks – these all affect support of decision-making towards reducing technical risks. Most propositions for engineering design provide support in the form of prescriptions and strategies for modelling solution alternatives and evaluating their performance. While knowledge management solutions work well in supporting the design task, there were still significant issues: on the one hand, their effective use in decision-making was at best elusive, as their support focuses the long-term design activity on modelling and generating knowledge; on the other hand, approaches for decision-making tended to focus on making records about the decision process rather than on actually assisting designers and benefitting from their knowledge.

Conclusions

This paper aimed to understand the use of knowledge and the outcome of the verification of solution alternatives in R&D projects. Hence, it focused upon the interface between the choice of strategies for developing the principle solution and the use of design methods for verifying concepts making solution alternatives. A three-year case study of a medical device in industry formed the main data source.

The first finding of this study was the reappearance of failure modes upon the reuse of working principles across solution alternatives. Design issues manifested in prior alternatives were carried over to later alternatives that used components with similar characteristics and similar mechanical action. This was found to take place in the relationship between decision-making and design feedback, as the development of later alternatives usually started close to the date of a decision on ongoing alternatives. The identified cause was the failure of design feedback in learning from decisions, where characterizations of the failure mechanism and of the feedback on the expected mitigation diverged. Such failure occurred as a function of the reasoning elicited by methods used through the design process, where earlier methods usually provide measures of confidence with limited clarity as to which design characteristics give rise to that confidence and why.

The verification procedure used prior to the choice of alternatives for system design – as shown in Figure 4 – provided such information but at a high cost in resources, which made it impracticable for verifying several alternatives in the earliest tasks of concept development.

This study generated deeper understanding of the way knowledge about attributes of solutions not only influences decisions and development strategy, but also opened opportunities of developing knowledge of how to support the early verification of product designs. This finding points to a need for better knowledge resources, such as design records, to provide access to clear descriptions of the reasons for rejecting solution alternatives during concept development, and to ensure that problematic working principles are identified – and solved if feasible – prior to their reuse in further development.

We argue that these factors limited the effectiveness of development strategies such as set-based development and front-loading, and that these were due to shortcomings in the design reuse mechanism. These shortcomings were related to the following characteristics: first, the lack of clarity about constraints to design reuse and probable conflicts arising from the use of the past design in the new system; second, the shifting of priorities as solution alternatives develop in detail and constraints of design reuse are neglected; third, the variation of component and functional scope influenced by the variety of working principles used in managing the design process around product chunks; fourth, the fact that the mechanism of learning from failure in feedback falls short of informing current and future designers of the conditions under which a given working principle can be used; and, fifth, the lack of support in engineering knowledge to product verification based on confidence – which plays a major role in design decisions where there is shortage of time and lack of supporting information. These shortcomings have a major influence on the performance of design teams in managing the conflicts and constraints arising from the development of novel products with a wide variety of options.

The study reveals the need for structures of identification and reasoning that maintain their coherence as priorities shift throughout the design process, and that perform consistently in eliciting engineering knowledge and expertise, regardless of the level of information that is provided as input. Although this study is based upon a single case study – a fact which prevents its conclusions being generalized to apply to engineering design in several domains – , the value of this effort resides in the elucidation of circumstances in early design phases involving the effects of the actual use in practice of engineering knowledge.

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Requirements, development and verification of a design tool on design attributes for failure and success during early design phases

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Abstract

Assessing risk and reliability during early design phases is critical in safety-driven industries. This study aims to describe a design tool to codify engineering knowledge about attributes of solution alternatives. A prescriptive study was performed to develop the tool, followed by a verification study with interviews and design workshops to assess the ability to assist decision-making and knowledge reuse during early design phases. A taxonomy with types of information about robustness, reliability and safety was expanded to include information about the end effects of failures and successes of working principles. Also, the project documentation was found to be incomplete with respect to the variety of information types to define failure and success of alternatives. These findings led to a visual approach displaying several types of information about alternatives in a single view. The following factors were uncovered: while displaying several types of information, the tool was seen as naïve against preferences and political factors; designers were able to use the tool as reference for their decision and propositions of improvement; the tool provided them content for their refining their judgment throughout the decision task; and, designers successfully avoided the reappearance of failures while replicating successful characteristics when reusing designs. Hence, the design tool can be shown as improved support to using engineering knowledge for verification of designs.

Keywords: Design tool, engineering knowledge, concept design, alternatives

Introduction

Early design phases are critical in the development of innovative product designs. In this context, engineering knowledge in early phases underpins the work of design departments in establishing key characteristics of designs that will satisfy the preferences of their customers. The importance of early design phases as a subject of interest to academia and industry resides in the freedom to define or rethink intended product functions and how these are to be implemented (Andreasen & Olesen, 1990). This freedom to generate innovative designs has the drawback of significant uncertainty, as the solutions being developed are highly original, and this makes it difficult to use knowledge about current products to evaluate or predict the performance of new alternatives (Nikolaidis, 2005). New market opportunities generate requirements that current designs cannot meet, motivating the development of new designs whose implementation is uncertain. At the same time, design teams are required to evaluate concepts under conditions of uncertainty and make short-term decisions as tight project schedules exert a pressure to make such commitments.

Research in the field of engineering design, focusing the verification of functionality in product concepts, aims to make design teams aware of factors influencing the way design issues arise, and to promote improvements in the reasoning and the methods designers use (Cross, 1993; Pahl & Beitz, 1996). This field explores ways of eliciting and modelling characteristics of the product that enable designers to deliberate about and solve engineering problems. In this area, researchers focus upon the development and evaluation of methodologies for solving engineering problems, regarding the methods used, the lines of reasoning and the consequent courses of action (Andreasen, 2001).

This motivates us to explore the context of knowledge-based support for early design phases, with a focus on methods to evaluate the attributes of robustness, reliability and safety. Current methods of evaluating robustness, reliability and safety substantiate the addressing of design issues as they relate characteristics of developing designs to their implementation. This motivates the widespread use of such methods in industry, although most of them require thorough documentation for their application (Glossop, Ioannides, & Gould, 2005). In addition to this, much of this documentation is unavailable during early phases of design as it involves information only developed during detailed design (Marini, Restrepo, & Ahmed, 2010). Besides, current methods supporting robustness, reliability and safety in the design process also make significant demands on project resources and design expertise. For such reasons, there is insufficient understanding of how designers actually consider these attributes in relation to the design of solution alternatives.

In response to this problem, this paper aims to describe the development and verification of a knowledge-based design tool that supports the evaluation of solution alternatives during decisions in early design phases. The endeavour to solve design issues depends upon knowledge used by designers when asking for information to engage and fulfil design assignments (Court, Ullman, & Culley, 1998), which influences the choice of courses of action to tackle engineering problems. Such requests of information trigger a chain of knowledge consolidation regarding how design issues are handled, distributed and solved. This highlights the relevance of knowledge-based support to engineering design as a research subject dealing with the provision and management of the information needed by designers to tackle engineering problems. Nevertheless, questions remain on how design issues are elicited for decision processes; and how these are fed back from the verification of issues into the design process.

Previous studies of ours revealed the incompleteness of information from early design phases available for using current methods for robustness, reliability and safety (Marini, Restrepo, & Ahmed, 2010). The influence of the information requirements for functional verification remains a question of significant interest in regard to experimentation and prototyping (Thomke, 1998; Ulrich & Eppinger, 2002), and is of significant interest within the engineering design domain as design methods and engineering knowledge are often explored separately in engineering design research (Culley & Clarkson, 2005; Ahmed, Hacker, & Wallace, 2005).

This paper describes: first, the implementation of a knowledge-based design tool based upon an engineering knowledge taxonomy that encompasses different characteristics of information used by designers; and, second, the verification of how this design tool effectively works in assisting designers in judging solution alternatives in early design phases, using the information it provides about the performance characteristics of solution alternatives. The knowledge-based design tool is derived from the results of a longitudinal case study that follows the early design phases in the development of an insulin injection pen (Marini & Ahmed-Kristensen, 2013). The types of information contained in statements by designers who evaluate solution alternatives were identified forming the basis of the tool. Verification of the tool is based on the parsing of information from the industrial case study to the format proposed in the design tool, and on its use in simulating a design decision meeting with knowledge reuse to further development. This is carried out by the means of prototypes of the tool, which were assembled and verified in two steps:

- first, the overall verification of the tool; and,
- second, the simulation of a design decision exercise.

This paper is then divided into the following sections: Background summarises the current level of academic knowledge on the topics related to the problem dealt with in this paper; Method introduces the procedure used to extract and process the data from the study so as to attend to the proposition of this paper; Results presents the outcomes of the study; Discussion debates the findings in the light of recent developments in the field; and Conclusions reflects on the outcome of this study in regard to the contribution generated by this paper.

Background

Given the need to improve the level of confidence in the verification of solution alternatives, current knowledge about the codification and use of engineering knowledge needs to be reflected upon. The following circumstances affect the verification of alternatives on their suitability to design requirements:

- Firstly, uncertainty and ambiguity pervade the design process, flowing from the comparison of design requirements with customer needs through to the development of a design solution (De Weck, Eckert, & Clarkson, 2007). Novel product designs that become increasingly complex do complicate the effort of traceability across layers of product characteristics, from requirement through function to the component level. Considering the variety of solution alternatives and the uncertainty of their satisfying design requirements, concept development becomes subject to uncertainty and ambiguity (Schrader, Riggs, & Smith, 1993). In conceptual design, relations between design variables and across product subsystems are often yet to be understood.

- Secondly, it is likely that not all variables and their effects have been clarified prior to the development of the new product. This is then mitigated investing resources upon series of problem-framing, model-building and verification tasks during the design process (Thomke, 1998). In project management, the rates of over-budgeting, completion delays and abandonment are significantly high in product development projects, linked to shortcomings in the management of the ambiguity and uncertainty of novel solutions (Coppendale, 1995). To decrease the likelihood of unexpected issues, detailed project plans and early product models are suggested. Besides, major impacts on the product and the project can be averted by the concurrent development of several options with early testing.
- Thirdly, decisions are often prone to issues that increase risk in product development. Two types of decision-making influence the design process: one where all alternatives are compared with established criteria; and, another where alternatives are evaluated in regard to generic criteria, compared with and evolved against each other. Typical behaviour observed from designers involves the branching out of issues and alternatives in decision discussions, where criteria are updated along the emergence of situations, while previously considered options may be forgotten (Dwakaranath & Wallace, 1995). In addition to these issues, little time is dedicated for discussing the rank of criteria, and formal methods make limited influence on the justification of design evaluations (Girod, Elliott, Burns, & Wright, 2003). Thus, there is little support from methods to the decision process, for capturing the content of mid-term evaluations of alternatives, and making a structured set of decision criteria.

Girod et al. (2003) describe the process flow through decision-making. A comparison across several design teams undertaking decision processes is carried out, which identifies separate patterns: definition of criteria, generation of sub-issues, and the raising of evidence. A common pattern of decisions was observed to be made on a qualitative rather than on a quantitative basis; this involves the relative comparison of alternatives against each other rather than against structured criteria. The observations reveal that the decision process is often executed in an informal manner, according to a few generic criteria that are more relevant than several criteria that are more specific.

The occurrence of failures is linked to a lack of scrutiny of solution alternatives and to ignorance of losses from past mistakes (Petroski, 1994); a successful case of a bridge design is revealed, where past knowledge and the awareness of mistakes in past projects is contrasted with assumptions in the bridge design. The prediction of failures in designs during development is often hampered: too much effort to process information, a bias towards avoiding commitment, isolation and lack of coordination, and lack of confidence in methods (Busby & Strutt, 2001). From these factors, the lack of coordination and the effort of processing relevant information can be seen as symptoms of a lack of common understanding of risk and uncertainties from issues affecting product designs (McMahon & Busby, 2005). Current methods are mostly recommended for detailed design, as they comprise thorough component-based assessments, where detailed component characteristics trigger mechanisms of failure.

Current methods for robustness, reliability and safety can be divided on their approach to representing risks, regarding the following types:

- Methods addressing functional characteristics of systems, such as FMEA and HAZOP (MIL-STD 1629A, 1980; Kletz, 1997), embed part-of, from-to and cause-effect relationships in a sequence of fields within spreadsheets for recognising wear and failure mechanisms from intended and unintended operational use that is reasonably foreseeable; and,
- Other methods for scenario assessment, such as FTA and safety-barrier diagrams (Vesely, Goldberg, Roberts, & Haasl, 1981; Duijm, 2008), operate by identifying scenarios where failures may occur and by pointing out system units where defences may help to avoid failure.
- Safety issues concern damage to property, people, environment and society as a whole (Kozine, Duijm, & Lauridsen, 2000), so knowledge about safety is mostly contained in directives and standards to prevent hazards during the design process (ISO 14971, 2008).

The difficulty in predicting failure is increased by designers' lack of awareness of the knowledge available to them; this can be reused for the improvement of current products and for the development of innovative ones, by providing a structure to apply in new situations (Von Hippel & Tyre, 1995; Majrczak, Cooper, & Neece, 2004). Lack of knowledge reuse is only mitigated by experience, as it is experienced professionals who know where information resources are located, how to acquire them, and how useful their interpretation is in solving problems; it is by experience that designers learn to distinguish what available information actually tells them, and the feasible options (Wallace, Ahmed, & Bracewell, 2005). Designers were observed to make reference to personal or others' experiences to provide rationale for their arguments or to make analogy with their counterparts during a negotiation (Visser, 1995).

This kind of mechanism is essential in design teamwork when designers make decisions, by conveying that such knowledge has been verified by the means of fact. It may take place in the inter-personal level in a design meeting (Visser, 1995), or between a person and any information being sought as design knowledge. In the light of these thought processes, the complexity of employing current methods for robustness, reliability and safety means that, unless there is automated support or simplified protocols, it is very likely that designers will overlook causes of failure.

Literature establishes prior definitions for classifying information about R2S attributes in the design process, by the extraction of classifications from empirical data and their validation in dialogue with users in the field (Ahmed, Kim, & Wallace, 2007). Causal networks and generic information types were obtained from accident reports and interaction with design engineers about a few representative examples from practice (Busby & Strutt, 2001). The Engineering Design Information Taxonomy (EDIT) was developed through empirical research extracting generic types from information that is specific to individual design projects, and then validated through interviews with the design teams involved. This can be applied, for instance, to identify the types of design information emphasized across levels of design expertise in the product development process, which enables the mapping of dynamic networks of interfaces and issues in complex products (Ahmed, 2005).

Complex issues in system and product design, such as the evaluation of information requirements in current methods for robustness, reliability and safety also need classification. For instance, types of information for assessing reliability and safety of a washing machine were identified (Marini, Restrepo, & Ahmed, 2010), with partial reuse of the EDIT framework associated with knowledge of failures in machinery. Such frameworks emphasize the structuring of knowledge, the management of available content; their shared acceptance provides a basis for developing better communication (Sim & Duffy, 2003).

Knowledge-based support developed to assist the execution of design work can be divided into codified or personalized resources: the former mediate between people and information by modifying the delivery of information in circumstances and format that are more amenable to people's understanding and development of insight; the latter aid transactions among people by facilitating the conditions of dialogue towards solving design issues (McMahon, Lowe, & Culley, 2004). Codification approaches involve the interpretation of design models and their translation into presentation formats or written content that indicates or directly provides guidance for designers engaging in product development project. Design models and knowledge provide clues to extracting 'rules of thumb' and strategies by observing activities of designers throughout the design process, such as the definition of design principles extracted from long-term experience (French, 1994). Design principles become consolidated over repeated successful experiences carried out by groups of designers; they are often expressed as simple guidelines that advise on a parametric relationship or on the use of a design feature that favours a prioritized requirement.

However, it is the task of the individual or the team making use of the guidelines to assess their applicability for a given context, and the interpretation of design principles is heavily associated with one's own experience of situations (Lawson, 2004). The reuse of past designs, which engineers do intuitively, creates a shared language within a group of designers who have enough expertise to recognize cues to successful design strategies. However, this increases the possibilities of conflict between requirements to the product and changing team interfaces that change to accommodate new design requirements (Eckert, Stacey, & Earl, 2005). This is often because expertise among professionals does not always work in favour of standard or shared interpretations; due to the complexity of information on new solution alternatives during conceptual design, designers usually make intuitive commitments, which carry little understanding of the product but are deemed essential to satisfying its purpose (Gigerenzer, 2007). This reflects the use of heuristics as a cognitive shortcut when more elaborate formulations do not fulfil the need for confidence and adequate certainty to make a decision.

Another way of using heuristics is to follow expert behaviour and identify strategies that can be applied to improve communication between designers and to solve design issues – for example, extracting possible strategies to communicate issues and elicit solutions for them; these formed the basis of a knowledge-based design tool for guiding novice designers in the aerospace industry (Ahmed & Wallace, 2004). This is confirmed by research into design strategies with attributes of good examples as template for generating better solutions (Fu, Cagan, & Kotovsky, 2010). There, a laboratory experiment where engineering students perform a design activity showed that good design examples within a set of requirements elicited the development of more favourable solutions. Good examples in design promote analogical reasoning, which makes mental simulation reasonably affordable for people in pursuit of ideas to solve a design problem. The exploration of analogy and simulation also revealed that designers search for new functions to be carried out by existing working principles (Ahmed & Christensen, 2009). Currently, there is a lack of knowledge about how such behaviour can be better supported.

Method

This research intended to support the management of technical risks during early design phases in product development. This study deals with a medical device – namely, the dosage mechanism of a mechatronic insulin injection pen. The latter is characterized as a precision-mechanics device integrated with electronic components whose performance is especially sensitive to robustness, reliability and safety attributes because of the life-threatening implications of shortcomings in the dispensing of insulin to diabetic patients. Current methods supporting attributes of robustness, reliability and safety cannot be used within this scope (i.e. early design phases) because most current methods required detailed design information (Marini, Restrepo, & Ahmed, 2009; Marini, Restrepo, & Ahmed, 2010). Our study investigates the selection of alternatives and working principles, particularly with regard to design flaws in previous concepts. Knowledge reuse loops in the design process were found as critical for developing knowledge-based support to early design phases (Marini, Ahmed-Kristensen, & Restrepo, 2011; Marini & Ahmed-Kristensen, 2012).

These contributions report on a longitudinal case study – as shown in Table 1 – whose objective was to investigate complex relationships in the use of design information to evaluate robustness, reliability and safety attributes and their implications for the course of action in concept development. Compared to other studies about product development strategies in the automotive sector, the insulin injection pen differs in being a product with stringent regulatory requirements due to the immediate risk to human life in the case of failure. The case study involved an empirical study with the manufacturer of the medical device to gather concept design information generated over three years for developing and verify a design tool to support verification, decision-making and knowledge reuse to further work during concept development.

Information from the longitudinal case study consists of the design of the dose mechanism and the use of the measurement system in the insulin injection pen. Open-ended interviews were carried out with all the mechanical designers, one system engineer and the project manager. Semi-structured interviews were carried out with the mechanical designers only. Questions put to interviewees focused two types of issues: challenges and measures to manage technical risk (open-ended), and the rationale for selecting and rejecting design alternatives (semi-structured), to guide the search for information and validate the findings from documentation and reverse engineering respectively. Data collection was performed as shown in Table 1.

Table 1 - Case study on insulin pen (Marini, Ahmed-Kristensen, & Restrepo, 2011)

Characteristic	**Doc. Analyses**	**Rev.engineering**	**Interviews**	**Model/represent**
Case executed with actual project	17 partial/closure stage presentations	4 sketch sessions of work principles	5x open-ended on technical issues	9 function modules in all alternatives
Researcher observes project	5 technical risk stage reviews	20 alternatives of solution (concepts)	3 mechanical engineers, 1 system engineer and project manager	Several overview and close-up screenshots of alternatives
Longitudinal and retrospective study	14 feasibility reports on features	50 CAD variants with small changes	Not mediated, with video records. (45min each)	3 sequence/timeline development graphs
Comprehensive study of situation	4 matrices about set-based dev.	9 modules in system formulation	3x semi-structured on concept selection decisions	Total of 50 failure occurrences to reject
36 months from sketch to solution	Several reports from evaluations	61 work principles in all alternatives	Mechanical engineers: 2 veteran, 1 expert; Risk specialist	Total of 47 mentions to technical risks
Lead time launch in 6 to 8 years	Validated by interviews	Associated to interviews	Specialist as mediator, with video records (60 min each)	Developed upon interviews

As this study proposes support for design practice and the verification of its use in a situation of concept development, it can be understood as a prescriptive study within the design research methodology (Blessing & Chakrabarti, 2007). Document analyses were used to evaluate the findings and recall the data. Then, analysis and modelling were done to conceptualize the form on which incidents with solution alternatives were to be described in the tool. For the purpose of this research, the design tool was presented and refined as a software mock-up with regard to evaluating the user interface to collecting and registering data. Terminology and scenarios of use were modelled to suit the industrial context. After that, interviews and questions elicited suggestions on how to organize and implement R2S information on solution alternatives. The combination of approaches in use is shown in Table 2.

Table 2 - Methods of data collection used in the development of the design tool

Document analyses	**Analysis and modelling**	**Interviews and questions**	**Observation of meetings**	**Reverse engineering**
Documentation from the industrial case about the outcomes of development project	Modelling of fields and user interface to carry evidence of R2S issues from incidents in the industrial case	Two semi-structured interviews for evaluating usage characteristics of the design tool	One structured workshop-format interview to assess the use of the tool for decision-making among solution alternatives	Decomposition of information from the industrial case following R2S taxonomy
Documentation from records created with the tool and their use in the validation interview	Modelling of scenarios and terminology to suit the expected use of the tool by designers	A questionnaire to participants of the observed workshop about their impressions of the tool	One structured workshop-format interview to assess the use of the tool to provide knowledge reuse on outstanding issues in chosen alternatives	Comparison between outcome of the exercise with the characteristics identified in the original project

The development of alternatives was carried out iteratively throughout the study by means of trial-verification-improvement cycles. The tool was developed in three iterations, with different representations of types of R2S information. Internal evaluations were carried out by the research team, and the external evaluations were carried out in collaboration with the manufacturer of the insulin pen injector. The solution alternatives for the front-end developed through the study, and the information contained in each alternative, are displayed in Table 3. Interviews and observations were carried out during the last two stages with the format of workshops for the following purposes: to evaluate the approach as implemented in a software mock-up with example cases from the original project and use scenarios to evaluate ways of retrieving and using information; and, in the last stage, observations were made of a workshop with designers from the manufacturing company who were using a paper-based prototype to validate the use of the approach, followed by questions about its use.

Table 3 - Characteristics of graphic layout alternatives to implementation in records

	List_1	Record1	Record2	Record3	Record4	Record5
Project info	Alternative	Alternative	Alternative	Project, alternative	Project, alternative, milestone, date, owner	Project, alternative
Scenario types	Failure with winner	Failure and winner	Failure and winner	Failure and winner	Failure and benefit	Failure, benefit and counter
Layout	Datasheet	Card view in paper	Card view in paper	Card view in paper, tablet	Browse list, Card view in tablet	Card view in paper
Mock-up	Excel	Visio	Visio	Visio + PPT	PPT	Visio
Functions	Browse, search	View, plot	View, plot	View, browse, search	Browse, search	View
Verification	Research team	Research team	Research team	Interview by research team and expert at company	Evaluation by research team and design team at company	Proof-of-concept simulation by design team at company

The following information was considered for display with the tool:

- Information about projects includes the project being carried out, the development phase, and the authentication of each case;
- The scenario types involved describes cases in terms of negative (failure), positive (benefit) and best effect (winner) in solution alternatives;
- The layout used consists of the user interface design that embodies the organization of types of information from the taxonomy and the relationships between information types describing cases of design issues;
- The mock-up used consists of the software platform (MS-Excel ®) where the layout was developed and from which it was printed for presentation and evaluation by interviewees;
- The functions of the mock-up include visualization formats suitable to various ways of navigation through several cases;

The verification of the tool takes into account the procedure carried out to collect knowledge reuse about the proposed alternative and the people involved in the process. This was carried out in the proof-of-concept level by practitioners from the same manufacturing company, but situated outside the original project. The tool was verified in a paper-based version, to assess its functionality as evidence about solution alternatives in support of design decisions and effective knowledge reuse.

The procedure of designers was observed to validate the use of the design tool:

- firstly, using design records about early alternatives to support the choice of the best one; and,
- secondly, using records on the winning alternative to address outstanding flaws in R2S attributes.

Reverse engineering was performed in two iterations: firstly, all incidents with design alternatives were registered in the form of records; and secondly, the outcomes of the exercise, as registered by the participant designers, were analyzed in comparison to the principle solution of the original project. After the workshop a questionnaire was sent to participants: this was instrumental in verifying the validity of the tool against expert opinion – at least two designers that participated in the study were veterans with more than 10 years of experience in the company.

Results

The basis for this paper was provided by work from previous stages of this study (Marini, Ahmed-Kristensen, & Restrepo, 2011; Marini & Ahmed-Kristensen, 2012). Analyses about how information on alternatives was used during early design phases led to finding issues as motivations to propose a design tool.

Relationships between the alternatives, and the reasons for their rejection, were examined in the data; these revealed how design methods were used to generate information, and how this information was used to select alternatives and improve those that remained. The following areas of design practice in concept development were considered during the development of the design tool:

- Rationale for the codification of design attributes;
- Information and user interface in the design tool;
- Verification of the tool and use by practitioners.

In order to define the focus of development for the design tool, issues in the development of solution alternatives were assessed. This revealed two aspects of interest: first, the information transactions between design tasks during concept development; and second, the types of information being used in and through these transactions.

The collection of knowledge about these elements uncovered the following issues: the benefit to be gained by verifying solution alternatives towards decision-making and further courses of action during concept development; and the essential information needed to establish a basis for judging the value of alternatives and for improving their feasibility.

Rationale for the codification of design attributes

The development of the tool focused the types of information required and how these could be represented to convey knowledge about alternatives at the functional level. This involved the verification of design taxonomies with respect to the situation and the types of design knowledge involved in the industrial case. Design tasks involving the generation of working principles and their assembly into alternatives were analyzed by employing a process view.

To clarify the order and dependencies between tasks in design cycles, such process modelling was used to depict and formalize a description of how design cycles were carried out through the project, as shown in Figure 1. Tasks related to the generation, the evaluation and the selection of alternatives were distinguished in this representation, establishing the essential information being communicated to reduce the occurrence of failures and secure the feasibility of the resulting design. The process is illustrated in a control system analogy so as to denote the process of acquiring knowledge about design issues and improving the control over them with alternatives that perform closer to design requirements.

Early design tasks have been divided into four main sets according to their use and treatment of information: reference (Re) tasks involve the search and consideration of past designs and templates for executing design activities, such as the construction of models and/or their evaluation; generation (Ge) tasks comprise the creation and development of solution alternatives through the use of models and routines that convey properties of the intended design that will be evaluated against requirements; evaluation tasks (Ev) involve the use of methods, standards and procedure to assess the suitability of solution alternatives under design to the requirements set for the product; and selection (Se) tasks include the gathering of information and its processing towards decision-making on which alternatives should be rejected and which ones should be developed through the project.

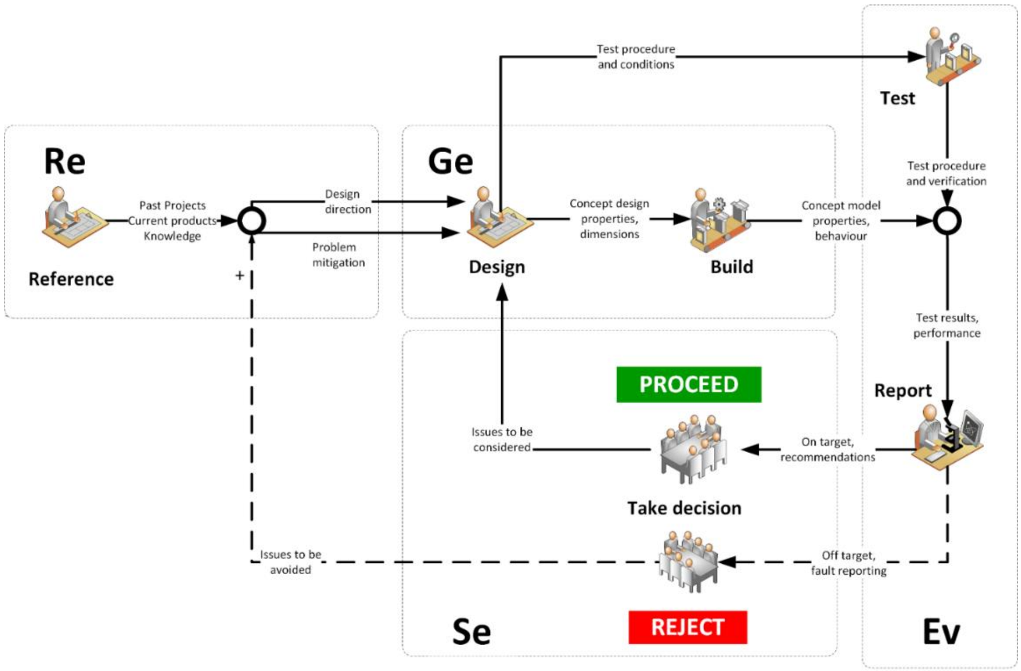

Figure 1 – Workflow representation of design tasks in early design stages

Relationships between tasks are depicted by arrows: design direction means the intended strategy for fulfilling the design requirements, which can be a preferred type of working principle or a product architecture deemed to improve the feasibility of the solution. As failure modes and their considerations unfolded from the documentation, it was found that the following relationships were essential to the evolution of solution alternatives towards the principle solution:

- The first relationship is between evaluation and selection, in terms of providing recommendations on the quality of solution alternatives or reporting on their weak points.
- The second relationship is between decision-making and other tasks proceeding with the project – to either look for new references to alternatives or to design functional improvements.

These relationships can be described as: the processing of information from evaluation methods to discussions in design reviews and decision-making, and from project assessments to design improvements, respectively. Both involve forming the basis for a design task from documentation about product designs, with focus on the transaction from evaluation methods to decision-making. However, the current study involved only the use of information about alternatives that have been approved – the rejected ones were stored in documentation that may not be consulted dismissed in further design phases.

As the project observed was developing technical attributes for the product, the taxonomy for robustness, reliability and safety was developed, evolving from the engineering design taxonomy EDIT (Ahmed, 2005; Marini, Restrepo, & Ahmed, 2010). Table 4 presents documented references to characteristics of the insulin pen regarding the taxonomy to robustness, reliability and safety as developed in the pilot case study. The information shared between tasks during early design phases was studied in order to define the requirements for the design tool. The assessment of dependencies between design tasks focused upon types of knowledge which were commonly used during the design process. This led to the taxonomy being evolved to reflect this new type of knowledge: see examples of statements about types of design information in the updated taxonomy in Table 4.

Table 4 - Revision of keywords classifying robustness, reliability and safety information

Keyword	Reference	Definition	Source	Example in project
Function	Functional basis [Hirtz et al., 2002]	Structured actions and system flows achieving a definite technical purpose	Feature definition	"The purpose of the feature is to allow the user to set and reset the desired dose size"
Product	EDIT [Ahmed, 2005]	Constructive elements, characteristics and relations from the designed product	Product rendering	"Dose setting: concept A1 consists of a torsion spring being tightened while setting the desired dose size"
Issue	EDIT [Ahmed, 2005]	Relations, characteristics and requirements to be considered during product design	Interview w/ engineer	"The needed torque for setting and resetting a dose is higher than the needed torque on current product"
Failure mode	Mechanical failure [Collins, 1995 Bloch & Geitner, 1990]	Processes and phenomena causing degradation of performance or failure	Evaluation reports	"Risk: "More than one IU resetting at the time; Mitigation: Optimisation of the click mechanism"
Event	Pilot study [Marini et al., 2010]	An occurrence where system properties and/or the functional state is changed	Evaluation reports, interview w/ engineer	"When a dose is set, a dosage tube is rotated up. When the dose is injected, the dosage tube, biased by a centrally placed dosage spring, advances."
Consequence	***Product dataset (Current research)***	***Outcome for people, assets and environment from the change of system properties and/or functional state***	***Evaluation reports***	***"[If there is] some dust or if the temperature changes or the humidity is high, then the sensor may have problems"***

The keyword definitions in the table are followed by examples taken from designers' statements made during an interview in the longitudinal study. These statements match the intended definition of each type. The additional content from the longitudinal study pointed out to the need of an extra category, namely 'consequence', whose information entails the characterization of probable outcomes from failure modes resulting from the failure to solve issues in solution alternatives.

The information found in documents and mentioned by designers in interviews was categorised against the types in the taxonomy. Here, the taxonomy was verified against descriptions of solution alternatives and their performance, using the same criterion that guided its development during the pilot study. This was carried out to establish the scope of information essential for judging the value of alternatives, and also about knowledge reuse from design decisions. Documents from the project database (see Doc. Analyses in Table 1) and interview transcripts were searched for references that matched existing types of design information, as in the classification of robustness, reliability and safety developed in the pilot study. For instance, the statement about 'problems in the sensor' considers the inability of the electronic system to follow the cursor accurately. This example demonstrates that functional requirements of the insulin pen are linked to the architecture of the product and its use; their development was carried out iteratively through design cycles.

In this regard, the failure to pinpoint the locations of failure modes from the industrial case derived from the ambiguity among the product architectures of several alternatives in regard to design parameters of the working principles. This is opposed to complete design models communicating design properties to an extent that either allows assessing the feasibility of alternatives with confidence, or allows actual verification of product properties against design requirements. Here, complexity across several designs takes place at three levels:

- first, the variety of working principles with component combinations that yield different modes of action;
- second, the variety of components responsible for carrying a single function in the device system; and,
- third, the variety of components that perform two or more functions performed by different functional surfaces.

Hence, uncertainty escalates from the combination of these kinds of complexity, and is aggravated by the ambiguity of novel designs for most components of the pen. Decisions made in the project related to the designers' perceived confidence in their ability to distinguish between promising and less promising alternatives once they had a certain level of detail. Clear functional descriptions were associated with statements of uncertainty as to whether alternatives would perform the given purpose satisfactorily – in particular about how mechanical working principles would perform. When the available information had a too high degree of uncertainty, only confidence assessments were possible based on the pool of expertise available to designers. If there was sufficient information to verify the design against design requirements, this indicated that few satisfactory alternatives would be selected, and further developed.

Table 5 shows the differences between information in documents from methods and the actual consideration of issues as done by designers. The study has found discrepancies in the amount of information between simpler and more comprehensive evaluations; then, the types of design information in use within statements from documentation and interviews were also found to be divergent; and, the actual use of the types as made in the interviews was found to comprise more than one type.

Table 5 - Examples of statements on solution alternatives from methods and interviews

	Meth.	Query	Example in method		Individual Types	Statement	Relation
Increments	**SETx**	**Possibility of ½ IU/U200**	**Table:** "Yes"		**Issue – Functional requirement**	"If there should be half increment, sheet metal gives less on that focus"	**Function → Product**
	EVA	*Dose button* / **dose set-up /** *mode change*	**(a)**"Range: 0 to *max* in 1 IU steps, possible dial up and down"	**(b)** "Flat torsion spring(...) Assembly status in CAD (...)"	**(a) Issue – Functional requirement** **(b) Product – Geometry**	"Half these teeth has to be very fine (…) talking about x.xx mm per unit"	**Issue → Product**
Reading	**SETx**	**Accuracy reading**	**Table:** "2"		**Issue – Product characteristic**	"The position of the dosage tube is what we are actually measuring"	**Product → Function**
	EVA	**Accuracy /** *sensor*	**Report:** "The position of the piston depends on the rotational position of the ratchet and the precise locking between the base part and the ratchet."		**Issue – Product characteristic**	"what you actually make the sensor of, it has to be without any gap"	**Product → Issue**

These comparisons highlighted the following issues:

- first, that more detailed information reflected an increased degree of concreteness to which design models reproduced relevant attributes to the satisfaction of design requirements;
- second, that the types of information in use in both documentation and interview statements were restricted to a biunivocal correspondence between information about the product and issues of its performance;
- third, while solution alternatives were verified at the functional level, functional considerations were kept implicit, as the product components themselves were used to convey notions of functionality;
- fourth, that further considerations, such as failure modes, were restricted to assessing the occurrence of limit conditions to failure, without further considering their implications.

In practice, documented statements mostly focused mainly upon a single type of information, without offering links to further design characteristics. Methods used more early did not provide all the types of information needed; methods from later tasks characterized all alternatives without considering end-effects. This made it difficult to assess the mechanisms behind the motivations for keeping or rejecting an alternative.

The motivations for rejecting solution alternatives were clear in the view of designers, which pinpointed the precise locations of design issues in components of individual alternatives. Yet there were cases where working principles that failed in previous alternatives were reused in later ones. At the same time, benefits from an alternative works well are at best linked to its being similar to a past design or to a previous alternative in the same project that is proven to perform well. The statement examples from Table 5 show that design issues were, at best, characterized in terms of issue-to-product and that functions are implicitly considered in the form of component names. This generates ambiguity across designs, as a standard component name such as ‘ratchet’ – for indexing increments – is used to define several component geometries in different alternatives. Hence, the information in methods either failed to indicate a clear mechanism of failure or benefit related to the working principle, or it prevented the identification of failure mechanisms helping ensure the rejection of the alternative also applied to the working principle that failed.

Information and user interface in the design tool

To help the verification of alternatives for decision-making, a knowledge-based approach was seen as the preferred means of support. Here, the taxonomy for robustness, reliability and safety was considered to encompass the relevant types of design information, including the necessary knowledge to justify decisions to reject or proceed with alternatives by explicitly describing their rationale. The tool was developed to focus on the types of information needed and on their structuring to present knowledge of how individual solutions performed. However, it is the availability of information to support decisions that has the major effect on the use of design methods; the information required depends largely upon the available levels of detail and clarity in representative models on the properties of the developing designs.

Current methods such as FMEA, FTA and HAZOP represent how failures originate and what their implications to attributes of product quality are. This enables a thought process that elicits more effective design thinking against modes of failure than the isolated use of individual representations such as text, formulae or drawings. Based upon this, and following the rationale from the previous section, the design tool was intended to display several characteristics of the product and at the same time declare individual design issues in single views. From the link between function/working principle pairs and the product architecture, the layout was intended represent the working principle as part of the alternative and as associated with a functional definition linked to physical modules in the assembly of the system. Along with this representation, the other types of information were intended for presentation with brief descriptions of each type of information associated with the design. Based mainly upon the rationale for the tool, records about alternatives were intended to suggest relationships between different types of information in individual design issues, to provide an overview of why they occur and of the effect they have on functional requirements; at the same time, the visual format was intended to enable comparison among several cases being presented, so as to provide support to design decisions in situations where uncertainty permits only confidence-based judgment.

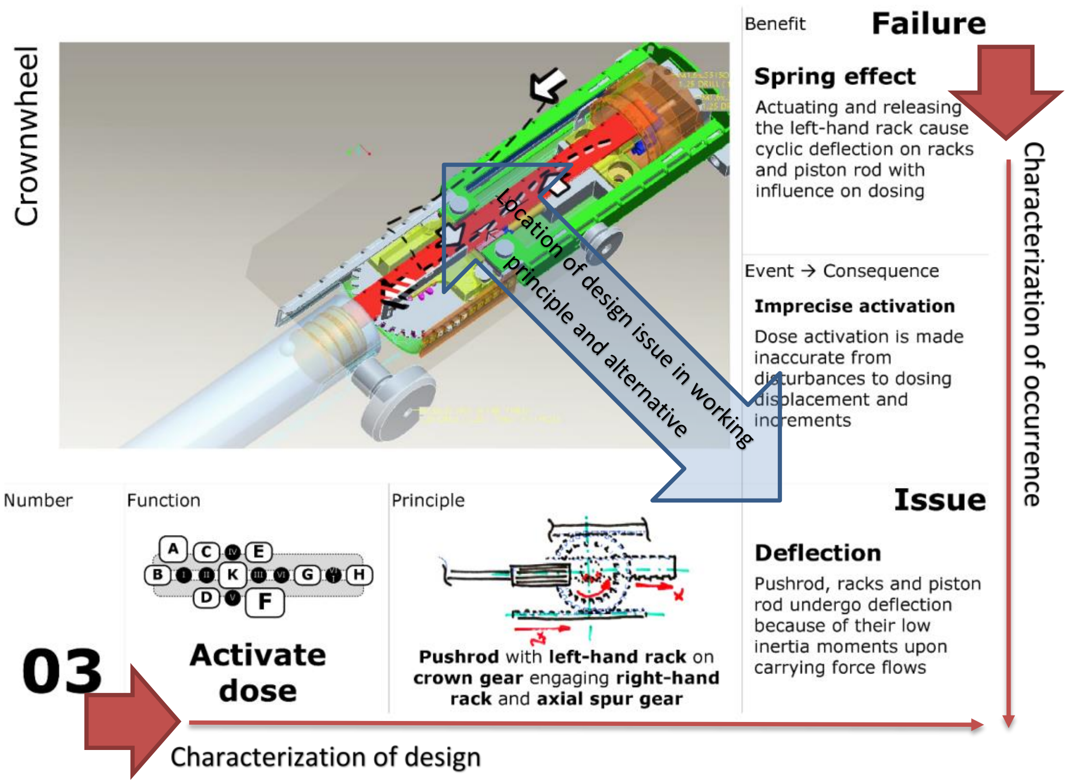

Figure 2 - Alternative layout for records on early design stages – Record_5, card view

The layout in Figure 2 constitutes the final layout proposed for individual cases of failure and success; this evolved from previous layouts that experimented with the order of information elements from keywords in the taxonomy along the natural reading direction from upper left to lower right. The information about solution alternatives is put together according to the working principle being illustrated within the solution alternative; icons representing geometry, kinematic and interface properties represent the working principle of interest that is related to the individual design issue being described. The concept here consists of displaying an individual design issue to be verified and subject to deeper evaluation of individual function/working principle pairs. The same structure was used for all records; by characterizing a single case, this format aimed to provide information about how a single function/working principle works in a specific design issue. This layout characterizes individual design issues, with text describing the mechanism by which alternatives work against design criteria; the graphics and text describing issues and modes of action improve the accessibility of information being communicated to designers.

__Verification of the design tool__

The design tool was evaluated by the partner company, i.e. the manufacturer of the medical device. The aims of the verification of the design tool were to:

- Test the usefulness of the proposed support; i.e. reducing repeated failure
- Identify issues in the use of the tool;
- Identify characteristics to be discussed;

To verify these characteristics, the design tool was verified through a sequence of steps that involved increasing interaction with practitioners:

- The first step focused verification of the design tool's user interface; and,
- The second step focused the verification of its use by designers.

In the first step, a preliminary layout was evaluated under expert review (open-ended interview), focusing upon the types of information to communicate design issues and the attributes affected. The expert acted as a company-wide consulting reference for risk and reliability topics, facilitating risk assessments and improving current practices. On receiving his knowledge reuse, the tool was prepared for a team-based expert review (semi-structured interview) on the information format and how it could be used during concept development. Participants in this meeting included one designer with more than 15 years of experience, one project manager with 10 years of experience and four other mechanical designers with an average of five years of experience. The expert reviews took 45 min and 1h 15 min respectively; the second expert review included 30 min. for presenting the format and scenarios of use. Information from these reviews was recorded in minutes of the meeting and then transferred to a partial report.

The second step was carried out with knowledge reuse from the previous interviews that supported the preparation of a design task simulation, involving the review of alternatives described in a paper-based version of the tool. The design task simulation took 1h 15 for the decision part and 45 min for the improvement part, then being observed and video-recorded. The task involved two parts:

- The first part involved the selection of the alternatives best suitable to their understanding from information in the records supplied; and,
- The second part involved the suggestion by designers of improvement ideas to robustness, reliability and safety against outstanding issues in the alternatives that remained.

The verification was done by the risk expert, one expert mechanical designer and two other designers with four years of experience, who made their assessment through questions, asked personally and by e-mail questionnaire.

The next sections present the verification process of the design tool; this was structured upon the evaluation model proposed by Kirkpatrick (Boyle & Crosby, 1997), which is composed of the following levels:

- ***Reaction*** considers the response of the participants to the method;
- ***Learning*** considers how participants learned to use the method and what they learned from it;
- ***Behaviour*** considers the change of attitude in participants based upon what was learned;
- ***Results*** considers the impact of the method and the change of behaviour in the organization learned;

The evaluation of the design tool covered mainly the topics of reaction, learning and behaviour; the impact of the method and its validation were not obtained due to the need for further work (Ahmed, 2001), which was not feasible in the timeframe of this research. The reaction of participants was assessed from the notes of the expert reviews and from the email questionnaire that was sent after the task simulation. Learning was assessed in regard to their perception of usefulness and intuitive use of the tool, evaluated in the email questionnaire after the task simulation. The behaviour of participants in using the tool was followed by observing the references through the video and skimming through the notes made by the participants. Results compare between the outcomes from the task simulation and from the original project: preliminary validation comments about the suitability of the tool to design work.

Reaction

The reaction from reviewers and participants was obtained by assessing their overall attitude towards using the tool as a support of their design practice. During evaluation sessions, participants were proactive in giving their opinion about the tool; designers present at the evaluations found that the layout and the navigation was appropriate in regard to the search and retrieval of information about solution alternatives.

However, there was a clear relationship between expertise and degree of acceptance:

- Novice designers valued the tool's attributes of communication and interaction;
- Designers with intermediate experience liked the visualization of design issues in their causes and implications together;
- Experienced designers thought the tool was naïve in terms of individual preferences, personal attachment and factors of pressure.

From previous research, it is known that experienced engineering designers are able to relate issues together (Ahmed, Wallace, & Blessing, 2003). All participants in the evaluation sessions agreed the tool provided a better degree of information about solution alternatives, and the criticisms offered were constructive about providing positive knowledge reuse towards improvement of the tool. Novice and intermediately experienced designers desired more information about the relationships between neighbour components in individual issues; they also pointed out the need to authenticate individual issues by providing personal references, where they felt the tool was good at navigating through solution alternatives and discussing strategies to improve them.

Learning

The learning aspect was assessed by observing how designers used the design tool throughout the task simulation, and asking participants what they thought of its usability. Designers found the grouping of several information fields about individual issues into solution alternatives to be a useful reproduction of their thinking; suggested improvements included the consideration of individual issues on the propagation of their effects complementing the escalation aspect. In practice, the information about individual issues was seen as a natural reference for justifying the decisions made and as a basis for suggestions of design improvements to address issues. Participants felt the tool offered sufficient information for their task, as they used references to individual design issues to justify their decisions; designers felt pressed to adopt a single strategy to solve an individual design problem, due to the characterization of individual issues by a single escalation mechanism (see arrows in Figure 3). At the same time, the interface helped designers to make intuitive assessments about the solvability of individual issues. The expert designer said "the tool helped to keep focus on technical risks"; thus alternatives less difficult to solve were chosen.

Behaviour

The behaviour of the participants vis-a-vis the tool was obtained from observing the participants during the task simulation and analysing the results from the notes they made, including the records with improvement suggestions. Hence, the participants' engagement with the use of the tool, and how this supported decisions and improvements, was assessed. To this end, the task simulation was set up with records of failure and benefit from early alternatives in the original project. The participants formed a team with assistance from the risk specialist inside the company, to use information about the alternatives as recorded in individual issues presented in card views such as that from Figure 2, and were asked to explain their decisions about design alternatives. Designers were given help sheets with example definitions; an introduction about the task simulation was also given. Information about alternatives was given in the form of individual card views, accompanied by original pictures of solution alternatives selected from the corporate product database. Designers documented their decisions, stating the main reason for rejecting each alternative and its ranking.

A decision timeline, shown in Figure 3, was generated on the views by participants about individual issues (alternatives coded as letter-number pairs) and their originals (Or), along with references participants made to taxonomy definitions (Df) and their consultations with the risk specialist (Fa). The figure shows the actions of participants while using the tool to assess and take decisions, as follows:

- *Browse alternative* denotes the action of participants in browsing through different cases of the same alternative and observing the model visualizations along the information in text fields. Here, participants viewed the cases available for obtaining a preliminary overview on qualities of the alternative.
- *Evaluate alternative* means that participants were now observing the cases of an individual alternative more intently. Then designers examined alternatives with increased focus on assessing the effect of the cases on the feasibility of functional requirements.
- *Analyse alternative* indicated that designers read the cases in records, seeking to ascertain the impact of design behaviour on requirements in cases of doubt. That was the situation where the participants needed to consolidate their judgment.

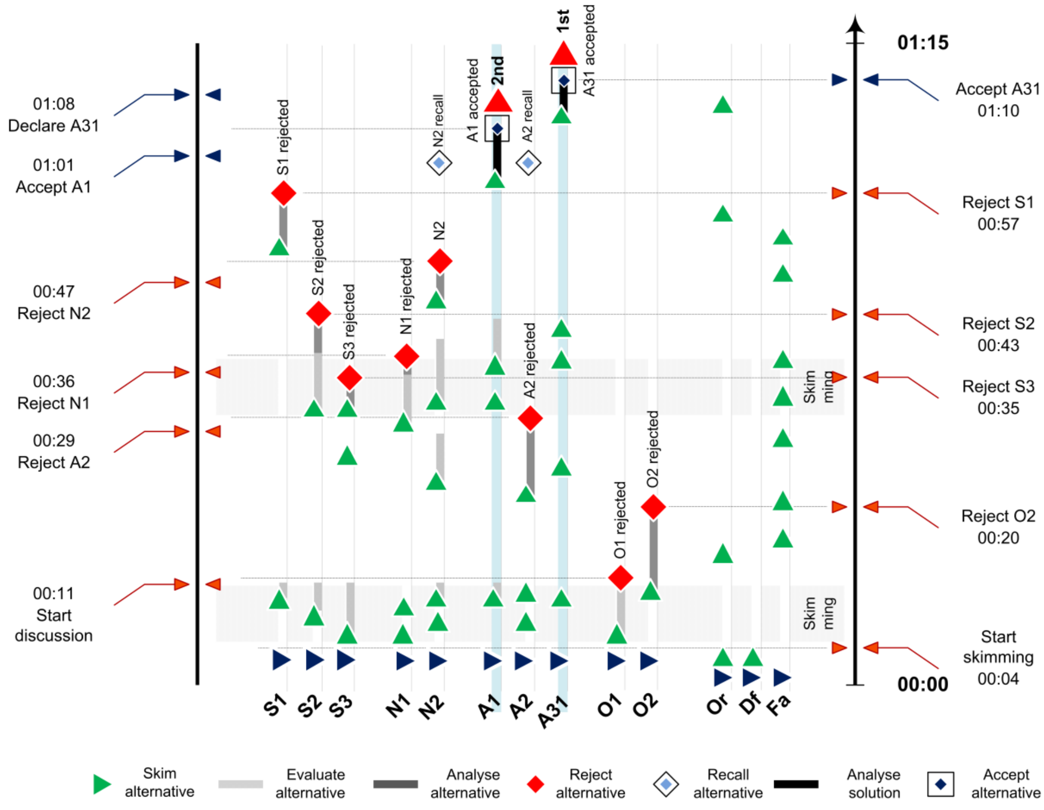

Figure 3 - Decision timeline across alternatives with designers using the tool

Other behaviours exhibited by participants concern attaining a degree of judgment that allowed a shared decision on individual solution alternatives:

- *Reject alternative* denotes the occasions when participants share the conclusion about rejecting an individual solution alternative. Designers share a degree of confidence about the view they formed, where an individual alternative is not worth pursuing because it would cost too much effort to solve its problems.
- *Recall alternative* denotes the occasions when participants find a case previously browsed and return for closing in on their judgment about the alternative. In this case, participants feel the need to confirm their assessment by ascertaining themselves their interpretation of the records.
- *Analyse solution* means designers viewed more intently the cases of the alternatives left as possible candidates, to form a detailed picture of how its performance was more satisfying than the others, i. e. that its performance was closer to functional requirements and that its problems were easier to solve.

Such actions have a consistent characteristic of being decision behaviours, where designers did as follows:

- Engaging with other alternatives when they reached a conclusion that the solution (i. e. the set of working principles) was not feasible;
- Refining their judgment upon the need to ensure that prior actions met their own criteria for the selection of suitable alternatives; and,
- Consolidating their judgment when they felt all alternatives they had met their view of functional requirements.

Then, the behaviour exhibited by participants could be followed as presented in Figure 3: the relative position between actions across the decision timeline shows patterns of interest in regard to the use of the tool. Firstly, participants browsed through all alternatives: here, they made two outright rejections as the renderings of the alternatives along the problems they have shown were fairly obvious indications that the designs being displayed were not feasible. Two browsing loops were carried out during the task simulation: the first was done in order to make an overview of all alternatives available and look for opportunities in the alternatives with obvious indications that the problems involved were not solvable; the second involved evaluation and analyses of individual cases of solution alternatives, in order to generate a basis for rejecting other alternatives that designers found interesting, but which they deemed to require too much effort and which in their experience were not feasible. The decisions occurred more or less at the same time as participants looked at original illustrations of the alternatives involved and consulted the risk specialist. These consultations were done in time spans of up to 20 seconds, indicating they needed clarification about the mechanisms of individual cases.

Secondly, participants started browsing and evaluating the other alternatives available. They consulted the risk specialist whenever they felt that the browsing of records did not offer sufficient basis for a safe judgment, then they started analysing the alternatives more intently to reject the alternatives which in their view did not satisfy their criteria on functional requirements. The consolidation of their judgments in rejecting alternatives like S2 and N2 in Figure 3 was carried out after analysing individual cases and consulting the specialist about their mechanism. As designers moved from discarding alternatives that did not work well to comparing those that were closer to functional requirements, the risk specialist was no longer consulted. Neither did participants look for further sources to support their judgment, which meant that records were now describing their own appraisal of the characteristics of alternatives.

After rejecting most alternatives, participants recalled two of these as they needed to ascertain that the mechanisms of failure and success with respect of effort vs. benefit to justified their decision in rejecting the alternative. Then, with three alternatives remaining, designers felt more comfortable in making their judgment, in which they felt all alternatives could meet their criteria on functional requirements and they could then judge the alternatives based on the least effort necessary to achieve functional requirements. Ultimately, participants chose the alternative that constituted the basis of the final principle solution from the original project; the other two alternatives that were finally dismissed had working principles which the participants knew about, but of whose suitability to the criteria set for the decision were uncertain.

Results

The result in terms of confirmed benefits and rejected failures in the decision is shown in Figure 4, Figure 5, and Figure 6. The figures represent the comparison of cases seen by designers throughout the original project and of the decisions taken by designers during the task simulation. The results focused upon assessing whether the tool could reduce repeated failures across alternatives. The decisions by designers effectively involved alternatives up to A4 in the Figures 4, 5 and 6. Other alternatives from A5 onwards shown in the figures represent attributes of alternatives in the task simulation that were maintained or prevented in comparison to later alternatives in the original project. The figures display comparisons of positive and negative attributes of solution alternatives, denoted as design benefits and reasons to reject respectively. On the one hand, a design benefit that is repeated indicates a certain set of functional attributes that is achieved and consolidated in a design strategy. This is consolidated when this repetition of design benefit is associated with individual working principles that are reused in subsequent alternatives. The comparison between the design benefits obtained in the original project and the design benefits being assessed in the task simulation considers whether design benefits could be associated to winning alternatives. In the other hand, a reason that is repeated indicates a failure to learn the mechanism of failure from a solution alternative to a subsequent one. This is clearer when such reasons to reject occur along the reuse of certain working principles that are inherently weak. Reasons to reject solution alternatives usually originate in mechanisms of failure that configure a particular design's deficiency in performing up to functional requirements. The repetition of such causes in other alternatives means that the physical principle from which the mechanism of failure originates is yet to be fully negotiated by designers; if this is tied to a particular working principle, it indicates that a certain component (or combination of components) from which this mechanism originates is reused through alternatives because prior decisions and strategies overlooked the physical issue. The comparison between reasons to reject in the original project and reasons to reject being assessed in the task simulation considers whether these reasons to reject could be prevented and/or mitigated.

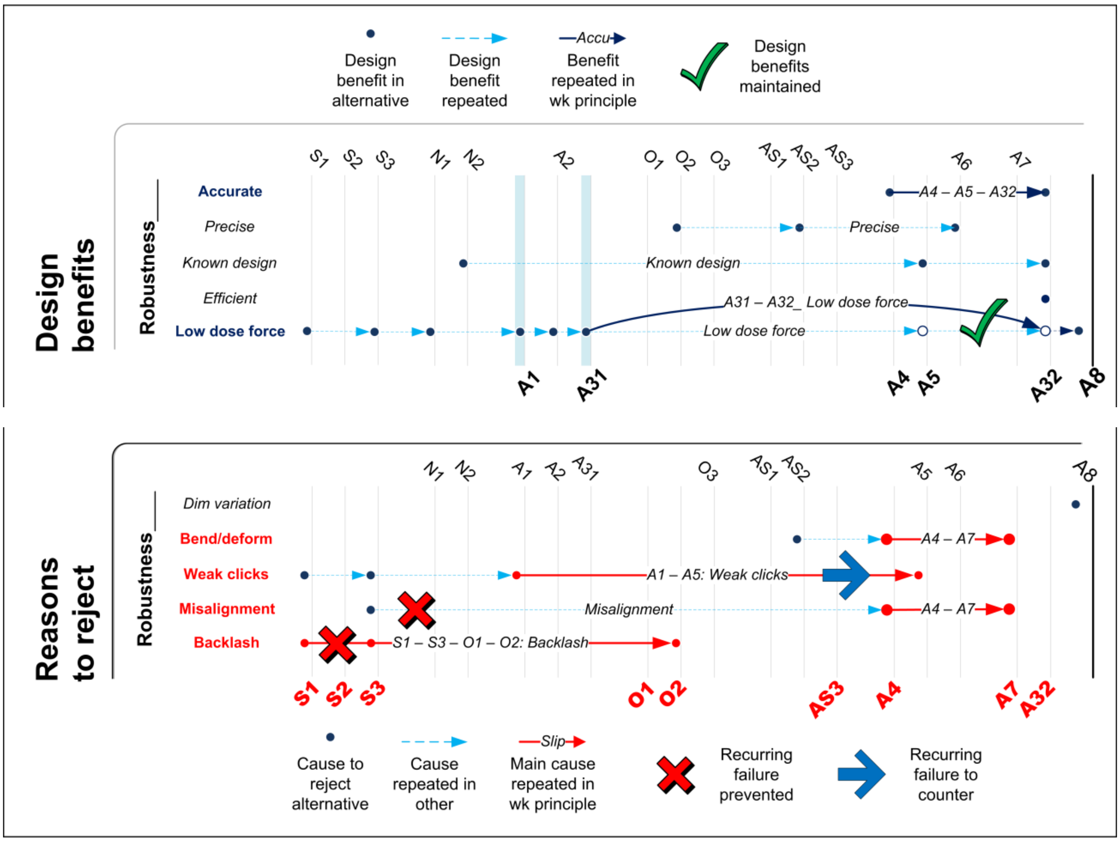

Figure 4 - Robustness attributes in solution alternatives with the use of the tool

The repeated failures from A4 to A7 were not considered because the alternatives between O3 to A8 were not included in the set of records used by the team. The *weak clicks* failure, in the left hand of Figure 5, was assigned among those to be countered in the next phase of the exercise, taking into consideration that the alternative that carried it was accepted. Other failures such as *misalignment* and *backlash* were effectively avoided by using the tool. The repeated *accurate* benefit was not considered, as the alternatives that carried it from A4 onwards were not included in the exercise. The *known design* benefit carried by N2 was discarded, while the benefit of *low dose force* – for the user – was effectively carried over from A31 to A8. This benefit was carried over the selection of A31 as the best alternative among those available for selection. The fact that benefits such as *accurate*, *efficient* and *precise* were absent from alternatives in the exercise means they were associated with detailed characteristics of the system, rather than characterizing working principles *per se*.

The timeline of decisions considering reliability issues is shown in Figure 6. No occurrences of repeated failures in later alternatives were found in this attribute. Occurrences of failure linked to working principle were effectively avoided by rejecting O1 and O2. The single occurrence of *spring effect* was also avoided upon rejection of S1. The occurrences of *parts break* and excessive *friction* were carried on upon being considered solvable. The repeated benefits of *low torque* and *low friction loss* were carried over from the accepted alternatives (A31 and A1); this also happened to the benefit of robust limiter which was not related to principle. The benefit of being *on par to* (at the same level as the current product) was not carried over, and the benefit of *no side-effect* was disregarded, as the alternative that carried it was absent in the process. Figure 6 shows that early alternatives carrying solvable reliability failures were carried over with the use of records, while other failures not considered solvable were discarded. The alternatives with unsolvable reliability issues were rejected in the beginning of the exercise after brief evaluation.

In the selection of alternatives, safety failures motivated outright rejection As shown in Figure 6. The occurrence of lack of friction was not considered as the design that manifested it was not included in the records. All other occurrences of failure were effectively avoided by rejecting the alternatives that manifested them first. Although the *slip* failure was not related to any working principle, it was rejected in all alternatives that manifested it up to O2. The repeated benefit of *safe*, referring to a general aspect, was not considered, as the alternatives that carried it – from A4 onwards – were not included in the exercise. All other safety benefits such as *effective end-of* and *no drawback* were carried over upon the resulting selection.

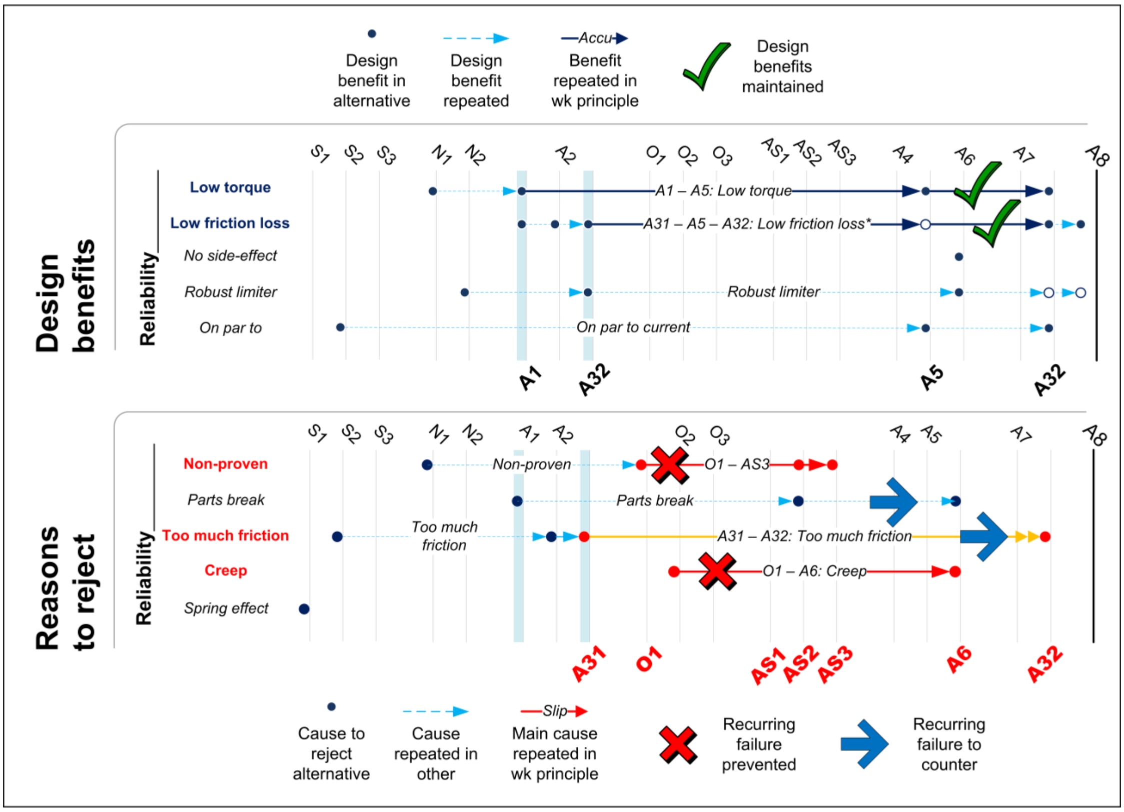

Figure 5 - Reliability attributes in solution alternatives with the use of the tool

While the *no drip* benefit was not related to any specific working principle, it was also carried over upon the selection made with the records. The evaluation demonstrated that early alternatives carrying safety failures were rejected with the use of records. The benefit of '*safe*' was not observed as a decision, as there were no early alternatives with the attribute. All other benefits that were identified in the remaining alternatives (A31 and A1) were carried over with the decision to new designs. Hence, the records supported the identification of issues with safety consequences.

For the decision-making part, the task simulation with the design tool yielded comparable results to the original project, which was encouraging. In regard to robustness and reliability attributes, reasons to reject were identified and divided into those that were unsolvable and unacceptable, and those that could be solved by design intervention in further work – the latter being due to the characteristics of the method, which elicited improvements in the outstanding alternatives. Design benefits were linked to fine-tuning design details such as the characteristics of material and component interfaces, as a single benefit was carried over from the choice in the task simulation. Design benefits to reliability attributes that were linked to working principles were successfully carried over in the decision made by participants during the simulation task, whereas those without such relation were not maintained. Reasons to reject linked to safety were deemed unacceptable in all cases and if they occurred resulted in outright rejection of the alternatives. Design benefits to safety were then successfully carried upon the choice made in the task simulation.

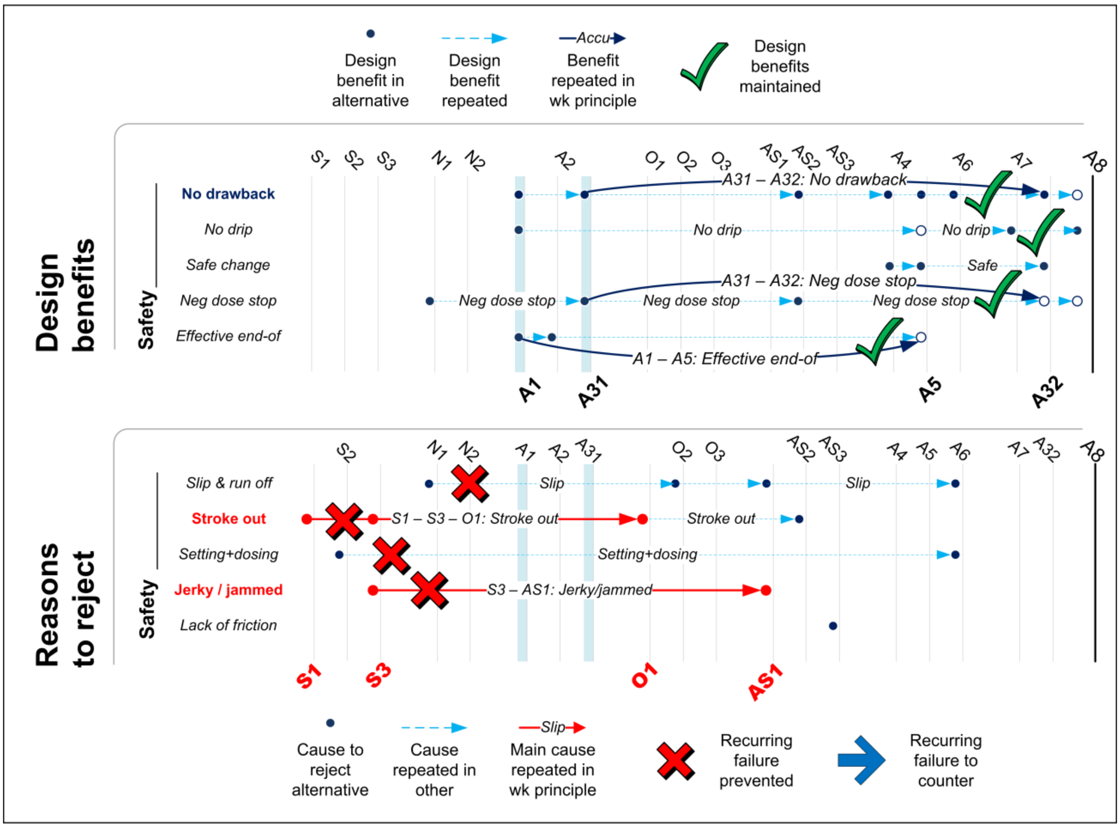

Figure 6 – Safety attributes in solution alternatives with the use of the tool

In the second part of the task simulation, participants were asked to assess the outstanding issues in the chosen alternative and suggest design improvements to them, referred to as countermeasures as shown in Figure 7. These were intended to prevent the repetition of mechanisms of failure which could be reasons for rejecting further solution alternatives, by forcing designers to learn and assess mechanisms of failure they consider solvable in winning alternatives from prior decisions. Countermeasures were seen to involve switching from one working principle that originates a mechanism of failure to another working principle that is known to prevent that particular mechanism – shown by green arrows in the upper part of Figure 7.

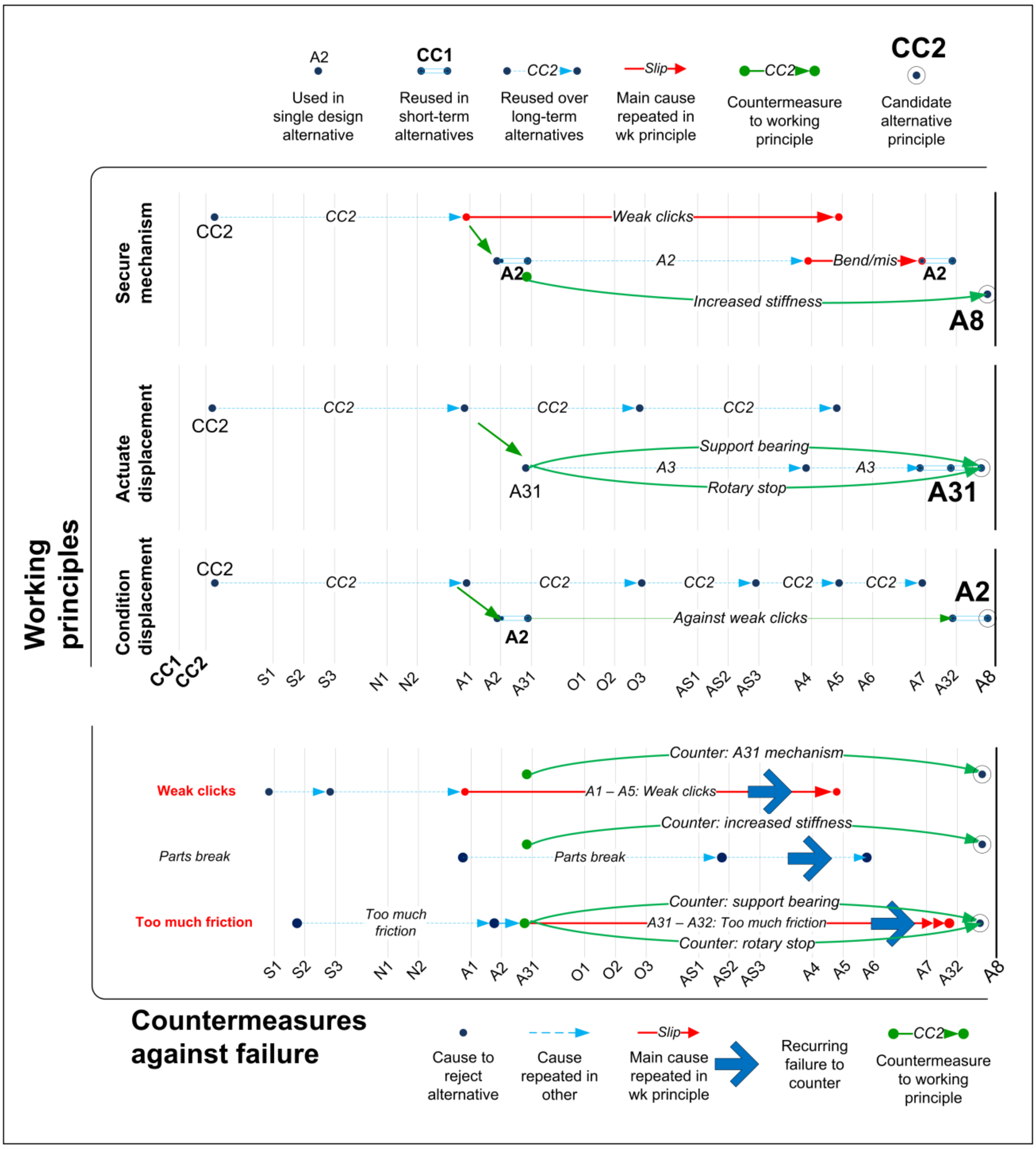

Figure 7 - Countermeasures proposed by the design team during the exercise

The other arrows confirm the character of the working principle selected, in regard to its relationship to the working principle used in the resulting solution principle from the original project.

The results link the outstanding issues in the chosen alternative to the similarity between the proposed design and the design characteristics of the solution principle A8. The lower part of Figure 7 shows the reasons to reject solution alternatives that were prevented by the countermeasures used. The similarity between the suggested countermeasure and the winning design (by the partner company) was verified from the output generated by participants in the second part of the task.

Three types of countermeasures were found this exercise:

- First, a change in working principle to a form similar to that found in solution principle A8;
- Second, switching from one accepted working principle towards the winning alternative;
- Third, improvements in working principles of the winning alternative.

The first countermeasure involved taking advantage of material properties of an internal component, which was not associated with the working principle. The second countermeasure involved comparing the acceptable alternatives and determining the best in regard to functional requirements. The third countermeasure was carried out by intensive examination of component and interface characteristics of the current working principle, whose shortcomings were to be alleviated. All countermeasures proposed in the exercise were found to be effective in incorporating the knowledge from design records as reference about outstanding failures, and in eliciting characteristics of the solution principle that were effective in solving the issues described in the records. Designers effectively used the records as sources of consultation and reference in their proposed countermeasures. These results motivate a positive assessment of the approach of design records, an approach whose performance in preventing recurring failures was found to be valid.

Discussion

The discussion about the requirements, development and verification of a design tool to codify information about failures and successes of solution alternatives in early design phases involves three different views.

Verification and improvement of solution alternatives

The first view regards the context of the design activities verifying and improving solution alternatives throughout concept development. Here, the connection between failure modes motivating the rejection of alternatives and the use and reuse of working principles was explored in previous studies. It was found that design information has to be sufficiently detailed to permit designers to analyse relationships among parameters of working principles. Studies of the design process used in the automotive and the oil and gas industries (Sobek, Ward, & Liker, 1999; Busby, 1998) show the need for data-intensive methods such as 3D simulations and probabilistic risk calculations in order to make appropriate assessments of robustness, reliability and safety. Early design phases, however, do not support the generation of extensive data sets about the geometry, material properties and boundary conditions of the developing product, or about the history, the frequency and the extent of all the events affecting the performance of the product through its lifecycle.

In response to this, many researchers in the community have developed a view of the engineering designer as artisan; in early design phases, the engineering design professional engages in creative work supported by experience and thereby develops solutions to meet certain functional requirements (French, 1994; Mørup, 1993; Matthiassen, 1997). These advocate the use of engineering judgment and creativity to overcome shortcomings in the designs being developed, especially when the characteristics of the product still need to be defined. If one views the design process as a problem-solving activity, then uncertainty and ambiguity (Schrader, Riggs, & Smith, 1993) are significantly more evident in early design phases. In early design phases, the lack of information about how the product works makes demands on the engineering designers' confidence as to what they intend a product to be and how they intend to implement it. Experience nevertheless shows that successful judgment entails the use of knowledge reuse about prior solutions and the communication of the developing design – based on facts – to avert failure and the damages associated with it (Petroski, 1994; Gries, Gericke, & Blessing, 2005). This explains the success of traditional methods by the wider consideration of a product's weaknesses before it actually is built (Kletz, 1997; Kozine, Duijm, & Lauridsen, 2000), in a language that is amenable to wider reasoning. However, the ability to use these methods effectively depends on the availability of information and expertise needed.

In early design phases, both verification and validation of product design involve the apprehension of design intent and the confirmation of design requirements, on the prioritisation of customer needs, the selection of the fittest solution principle and the communication of the developing product (Maropoulos & Ceglarek, 2010). Product designers developing the insulin injection pen were able to identify failure modes quite early in the development process due to an all-out prototyping strategy (Thomke, 1998; Thomke & Fujimoto, 2000) which was enabled by low prototyping costs for both virtual and physical prototyping.

Table 6 - Comparative verification of the design tool codifying design information

Industry/ref.	**Design tool [this study]**	**DRBFM [Otsuka et al., 2011]**	**Reliability model [Smith & Clarkson, 2005]**	**Triplets [Kroll & Shihmanter, 2011]**
Type of product	Medical device	Automotive	Crane machinery	Hydraulic systems
Size, scope, no. parts	Small, whole product n x 101	Medium, subsystem, n x 102	Large, subsystem, n x 101	Medium, whole product, n x 102
Complexity	Low	High	High	High
Damages from design flaw at use	EUR x 107	EUR x 106	EUR x 105	EUR x 104
Methodology	Prescriptive study and descriptive II	Descriptive study II, industry practice	Prescriptive study and descriptive II	Prescriptive study
Type of method	Keyword-based fields in graphic card layout	FMEA-like fields in spreadsheet layout	Node-link-branch from flow diagram	Taxonomy keywords in form layout
Design phase	Concept design: evaluation of alternatives	Detailed design, engineering change	Concept design, iteration of alternatives	Concept design, generation of principles
Verification setting	Simulation task with industry practitioners	Actual practice in academia and industry	Simulation example with industry project	Simulation example with academic work
Source of information	Assembly cutaways, augmented with icons	Assembly drawings, component hierarchies	Exploded assembly drawings	Freehand sketches of product
Focus area	Eng. design, knowledge mgmt.	Eng. Design, DFx	Eng. design, DFx	Eng. design, knowledge mgmt.
Source data	History of failure and benefit attributes of alternatives in early design phases of an R&D project	Test case from industry using prototype, assembly drawings and design data	Test case from industry using assembly drawings, design data and project documentation	Test case in laboratory using manufactured product and reverse engineering
Authentication of performance	Comparison of practitioners in industry using the method and results from original project	Comparison between practitioners using the method and others using FMEA	Review of output from researcher by practitioner in industry	Supervisor reviewing output from primary author
Structure facilitates knowledge reuse	Blank sheet with same fields elicits improvement to outstanding issues in cases of alternatives that were chosen.	Fields in the spreadsheet for the view of designers about improvement needs in a given product design.	Structure and branching assessments intended to give knowledge reuse for making improvements.	Informal knowledge reuse from triplets guided by specific parameter-based design methodology.
Uses information types that are widely applicable	Structure is based upon industry-tested taxonomies plus generic information from traditional methods	Template departs from currently known FMEA format and follows a known set of procedures	Requires knowledge about specific methodology for branching from specific flow diagrams	Requires knowledge about specific design methodology using intuitive thought processes
Prompts designers to think about and improve designs	Keeps the focus on functional requirements; designers use cases as input for generating improved designs	Uses hierarchic structures to assess the impact of changes to existing product designs	Uses layout sketches and flow diagrams to elicit branching considerations about interface problems	Uses intuitive concepts to describe design characteristics and orient towards improvements

In spite of this strategy, however, causes of rejection of earlier alternatives were repeated in later designs due to the reuse of working principles throughout design iterations. The design tool was thus developed with a focus on aiding decision-making and knowledge reuse in early design, starting from the premise that methods in the original project for the new pen (Marini, Ahmed-Kristensen, & Restrepo, 2011) were used to characterize design alternatives by perception, insight and preference of designers. As seen in Table 5, motivations and causes for knowledge reuse issues were not specified in the project and issues were characterized as component + issue tags. While this confirms the view by Maropoulos and Ceglarek (2010) about design verification as capture of intent in early design phases, the scope of this verification is expanded and deepened to include the assessment of working parameters in a mechanical embodiment.

Codifying design information for verification

The second view regards the requirements for codifying design information towards verifying solution alternatives in early design phases. Here, the first requirement is that the structure of the tool must facilitate design knowledge reuse with the indication of possible improvements (Gries, 2007). A significant issue standardized design methods such as FMEA, FTA and HAZOP (EN 60812, 2006; EN 61025, 2007; BS IEC 61882, 2001) is their focus on storing information for later retrieval, rather a desirable approach to giving immediate knowledge reuse on design issues so that designers can work on solving them. The use of information about design attributes such as robustness, reliability and safety should consider the intrinsically iterative nature of the design process in its procedure (Pahl & Beitz, 1996; Ulrich & Eppinger, 2002); the design knowledge reuse that is inherently linked to this is an essential resource for quality, as information about warranty claims, product introduction tests, and test results informs about design flaws that were overlooked in early stages (Gries, Gericke, & Blessing, 2005). This potential is largely overlooked in new approaches to assessing the functions and working parameters of developing designs (Smith & Clarkson, 2005; Derelöv, 2008), as their procedure of generating a predictive model of the developing product design involves a linear task sequence.

The second requirement for the design tool is the generic applicability of the types of information and layout structure on which design issues are retrieved and discussed (Ahmed & Storga, 2009). Novel evaluation approaches generate a structure with specific codes intended to convey characteristics of the product in the interest of assessing its performance and feasibility. However, terms and concepts that exist in the application environment may be quite different from those defined by the developer for the practical use of the method. Traditional methods such as FMEA, FTA and HAZOP also have the shortcoming of not being amenable to a self-contained evaluation of the design issues being described; they not only require readers to look for detailed information in original design documents, but also require a significant degree of expertise in interpreting the information contained therein. The process of parsing foreign codes and detailed information to the actual characterization of design issues may create significant communication barriers, which aggravates any already existing shortcomings in design knowledge reuse due to misunderstanding and mistakes in interpretation; this undermines trust in design teams and hampers the effective use of design knowledge reuse for improvement (Busby, 1998). While the development of solutions with a higher degree of originality does benefit from flow- and data-based methods, these methods work better in interpreting and communicating the design intent (Maropoulos & Ceglarek, 2010) towards the treatment of design requirements. This does not accord with the situation addressed in this paper, as it addresses the verification of solution alternatives on their feasibility during concept development work.

The third requirement for the design tool is the characteristic of prompting designers to think about robustness, reliability and safety in a systematic way. Sometimes the assessment of design attributes is supported by facts whose knowledge is shared by participants; in others this knowledge can be parsed through episodic information recalled by participants (Visser, 1995) as a resource for sharing facts of experience that are relevant in a design discussion. When having to decide between solution alternatives, designers will rely on their experience and feeling to make a confidence-based assessment (Lawson, 2004). Such a situation necessitates shared understanding of the core characteristics of a product design; taxonomies and knowledge-based methods (Ahmed, 2005; Tumer, Stone, & Bell, 2003; Kroll & Shihmanter, 2011) establish core concepts that can be freely used as practical guidance in characterizing design issues. Such approaches constitute devices for communicating the attributes and characteristics of the solution alternative under verification. While design reviews of solution alternatives do not involve actual designing, they do involve evaluations which prompt design thinking, mostly as an argumentation process to discuss the pros and cons of currently developing designs. In this situation, codification structures for design information serve as resources for reviewing and making decisions about the designs that will be further developed. In this context, DRBFM (Shimizu, Imagawa, & Noguchi, 2003) assesses failure modes and proposes ways to mitigate them with improved elicitation of improvements in comparison with FMEA (Otsuka, Takiguchi, Shimizu, & Mutoh, 2011), which is due to the use of assembly hierarchies in support of information about individual components of the product.

Verification of the design tool

The third view regards the verification of the use of the design tool in design activities for the verification and improvement of solution alternatives throughout concept development. This concerns the assessment of how practitioners perceive the tool against its stated purpose, and its performance in regard to enabling designers to perform the intended task and the results they obtain from using it. For the purpose of this contribution, this view is to be stated in regard to the requirements mentioned above in a comparative perspective with other design tools prescribed for use in early design stages. The requirements of knowledge reuse communication, wide applicability of information and elicitation of design thinking will be discussed in terms of the contribution of each tool to guide designers in making confidence-based decisions and improving the effects of those decisions on currently developing product designs. The comparative verification of the use of the design tool is represented in Table 6.

The verification of the design tool described in this paper includes two viewpoints: first, an internal viewpoint regarding its use; and second, an external viewpoint regarding its comparative status against other approaches recently developed. The design tool described displays a structure that facilitates knowledge reuse for improving designs, based upon the recognition of working principles and their association to cases of failure and benefit in regard to functional requirements. The characterization of the design issues in each record was made in technical language from the area of mechanism design within the domain of mechanical engineering. In this regard, the performance of participants depended on their individual ability to apply the natural language description to their context and address the parameters they needed to handle. Participants' experience of previous projects constitutes a hidden source of knowledge. This may have lent them templates/procedures (Von Hippel & Tyre, 1995) on which to develop the newly generated designs – something which particularly applies to the experienced participant: he had worked in three prior projects on similar devices. This works by the effect of design expertise, which is seen to generate schemata and rules of thumb as shortcuts to solutions (Lawson, 2004). Regarding the potential for solutions, the issue field was seen as directing the way towards a given working principle, whereas participants wanted it to be less specific.

The tool also used fields whose concepts are widely applicable, especially in regard to the keywords of the occurrence characterization (see Figure 2), which uses a simplified form of reasoning that is similar to the one found in traditional methods such as FMEA and HAZOP. Statements about product functions were defined as components of a modular product structure and written in the systematic verb + noun form, similar to the functional basis (Hirtz, Stone, McAdams, Szykman, & Wood, 2001). This manner of using product function definitions, rather than the definition of feature (a performance that is expected by the customer) currently adopted by the company, was perceived as a hindrance by participants unfamiliar with this kind of approach. This relates to the view about the development of taxonomies from their conceptual form to their use in the application environment, where the effectiveness of the ontology in facilitating the use of existing knowledge is linked to how well it fits the current ways of practitioners in interpreting the definitions within the knowledge structure embedded in the tool. The participants' performance in using the tool – especially of those with less seniority and experience – was tied to the visual representation of solution alternatives as linked to the written statements describing the design issue and its escalation. This shows the effectiveness of the graphic layout in guiding designers towards an assessment by linking several units of information in the same view, in spite the mental stamina demanded from participants in carrying out the simulated task.

The tool prompted participants to think about and improve the designs they chose. The example sheet for suggesting improvements served as guidance for their thinking about how to suggest solutions for the outstanding issues they faced; at the same time, participants could use individual cases as a direct source for their thoughts about generating the solution. The results shown in this paper were tied to the frame of knowledge possessed by participants in the task simulation, namely that they were part of the same company and had informal contact with the product designers involved in the original project from which the cases were extracted. Furthermore, considering the effect of prior knowledge about concepts (Reidenbach & Grimes, 1984), their performance with the tool could have been affected by their prior knowledge of the designs in solution alternatives. Though the participants in the task simulation were not part of the original project team, they were nonetheless the latter's peers and could have obtained information about the concepts and the issues involved through informal meetings. By means of these informal contact networks, participants may have obtained an increased grasp of the issues involved in the designs under assessment, thus influencing their decisions. The influence of this mechanism could be more significant on good examples shared informally (Fu, Cagan, & Kotovsky, 2010).

Compared to other recently developed methods, the tool supports reasoning based on confidence as well as reasoning based on informal knowledge of the parameters and data that characterize product designs. This allows flexibility in the verification of alternatives in the level of functional requirements: as the cases assessed in the task simulation were collected from an ongoing project, the tool can reference designs from prior projects as baselines; creativity is encouraged as a consequence of knowing these references, because knowledge reuse is inherent to the tool. This is similar both to DRBFM (Shimizu, Imagawa, & Noguchi, 2003), whose protocol involves direct knowledge reuse from problems currently manifested in product design as impacts from changes, and to the use of triplets (Kroll & Shihmanter, 2011), where knowledge reuse is also inherent in the embedded thought process of the methodology thereby proposed. It is a faster improvement mechanism than the flow-link-branch approach employed by the reliability method proposed by Smith and Clarkson (2005), where a whole predictive framework has to be assembled prior to designers receiving knowledge reuse about the improvements to make. Robustness strategies make sense of designers' prior knowledge of robust design methodology and parameter design (Jugulum & Frey, 2007), but are less intuitive in improving working principles as demonstrated by examples rather than actual courses of action in developing robustness.

This is coupled to prompting designers to point out design inconsistencies by changing their way of thinking. DRBFM needs support from detailed design data and significant expertise, and focuses detailed design, with the parallel use of actual product assemblies and component hierarchy diagrams, where implicit knowledge about working principles by practitioners helps them finding the ways to solve the problem. The same applies to the robustness taxonomy, as it relies on parameter functions and component assemblies, where influences on the parameters involved are implicitly considered. This is also influenced by language that is understandable by designers, who need to interpret assessments in terms of changes in the concrete domain. The use of branching hierarchies from flow diagrams (Smith & Clarkson, 2005), offers a comprehensive report on potential improvements, but makes for time-expensive knowledge reuse, as designers need to understand the considerations in relation to the tool and associate them with the components they design. Triplets are simpler structures that were designed for even earlier stages, but lack examples of use simulation by practitioners.

The approach hereby developed contributes to the following aspects: firstly, it reduces the risk of reusing problematic working principles, as it prompts practitioners to think about designs and focus on reducing the possibility of failure; secondly, it drives the convergence of concept design towards an effective principle solution, as it makes immediate use of knowledge reuse eliciting suggestions for designs that solve outstanding issues; and thirdly, it provides support to people with less expertise, as it enables discussion and shared understanding with focus on the feasibility of solutions, based upon records of cases of failure and success. This ensures that practitioners quickly become familiar with the use of the tool; its advantage lies in showing all concepts together in a logical browsing/reading sequence that drives the focus of confidence-based assessments into intuitive evaluation of functional requirements.

Conclusion

This paper aims to contribute to a better understanding of the requirements driving the development of a design tool whose mechanisms of improving a design towards robustness, reliability and safety attributes are hereby verified and discussed. This creates new knowledge by sharing experience in the use of design considerations that are crucial for the strategic improvement of design practice. The process is also relevant, as it displays the reflection and verification of practical requirements that are essential to satisfying the strategic purposes of driving the convergence from several solution alternatives that display failures and benefits to a single solution principle that contains attributes that are of value in successful performance in line with functional requirements and design issues that are greatly mitigated and under control. The main conclusion of the study was the potential performance of the tool, as shown in this paper, in driving communication among designers and across decision and knowledge reuse tasks to improve product design.

The design tool used a content structure with the following characteristics:

- It is widely applicable in different design environments,
- It enables immediate knowledge reuse to improve outstanding issues, and,
- It drives designers to think of attributes in a systematic way.

The last characteristic applies to both decision-making and design knowledge reuse with improvements. This was found to reduce the repetition of failures across solution alternatives due to reusing bad working principles; driving the convergence towards better solutions by the means of using alternatives with a predominance of good attributes in the knowledge reuse stage; and driving design teamwork in the discussion of issues, as it provides a platform for consultation and shared understanding.

As this paper aims to discuss the requirements, development and verification of the design tool, the following findings also apply:

- First, the consideration of early design phases as a cyclic, iterative process forms a premise for the development of support along with the importance of decision-making and knowledge reuse towards the convergence of solution alternatives to the principle solution;
- Second, the assessment of documental information from the R&D project characterizing the influence of evaluation methods on decision-making and knowledge reuse has augmented the proposition of a taxonomy for indexing design knowledge with focus on robustness, reliability and safety, where a ‘consequence’ keyword was added to characterize the end effects of design issues in the use environment;
- Third, the comparison between designers’ descriptions that express cases of failure and benefit by linking different types of information in one sentence, and evaluation reports from project documentation that state different types of information in separate units, has driven the adoption of a content structure with focus on the simultaneous visualization of several information types in a single view.
- Fourth, the proposals that were evaluated and verified by practitioners in this study contained propositions to satisfy these requirements which elicited further suggestions of improvement towards enabling communication and improving the readability of the keyword fields in a single view, whereas experienced

designers found the tool as vulnerable to design politics and to argumentation by experts for their pet designs;

- Fifth, the tool was tested in a task simulation with a decision-making stage and a knowledge reuse stage, where designers found the tool useful; it kept the focus on technical attributes of the alternatives regarding the escalation or development of failures and benefits, respectively, by the means of a widely applicable set of fields included in its content structure, and prompted designers to think about designs in a systematic way with a view to recognising weaknesses and suggesting improvements;
- Sixth, the tool has the potential of reducing the occurrence of the reuse of bad working principles throughout design projects, and of driving the convergence of solution alternatives towards a solution principle by the mechanism of good templating, hence having a positive effect on the feasibility of innovative products;

Based upon the findings above, the authors argue that different considerations of the design influence each other; design flaws always happen as a result of a network of factors that take place at the same time and heighten the escalation and propagation of small inconsistencies with customer needs to form significant damage to quality and to manufacturing companies' reputation (Gries, 2007). Knowledge-based strategies need also to acknowledge the influence of factors such as designers' familiarity with concepts or information that is conveyed in knowledge tools.

As this study was carried out with an empirical approach and was based upon a single case study, it can not claim support to general conclusions. However, findings were compared to other case studies in other engineering domains. At the same time, the findings from an in-depth, in-field study focusing on the support of design practice yield valuable knowledge about descriptive research of engineering design and knowledge management, in regard to the factors influencing the development and verification of knowledge-based support tools for the design activity.

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Current methods to robustness, reliability and safety reviewed have shortcomings including the complexity of using them and dependence on expert input for mitigating uncertainty and ambiguity among solution alternatives. This research is carried out using case studies: an assessment of information requirements from reliability methods, and an assessment of how current practice influences concept development. Designers get in the situation of reusing working principles that are inherently flawed. To address this issue, an approach based upon individual records enables designers to failures and benefits from prior working principles, before making a decision, and improving the more suitable alternatives through this feedback. The use of individual records on failures and benefits of solution alternatives successfully averted the repeated use of flawed working principles and identified the effective design solutions of the outstanding issues.

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